EXPERIMENTAL

HIGHLIGHTS

NEWEST QUARKONIA RESULTS FROM ALL THE EXPERIMENTS @ LHC

MAY 20, 2025
BROOKHAVEN LABORATORIES, NY

SPEAKER: MARIA ELENA ASCIOTI | ON BEHALF OF THE ALICE, ATLAS, CMS , AND LHCB COLLABORATIONS

CMS

A.D. 1308 unipg DIPARTIMENTO DI FISICA E GEOLOGIA DIPARTIMENTO DI ECCELLENZA MUR 2023/2027

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J/ψ AND ψ(2S)

Eur. Phys. J. C (2024) 84:169
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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 4 October 2023 / Accepted: 12 January 2024

CERN-EP-2024-155
2024/06/21

CMS-BPH-22-009

Measurement of the polarizations of prompt and non-prompt J/ψ and ψ(2S) mesons produced in pp collisions at $\sqrt{s} = 13$ TeV

J/ψ and ψ (2S)

The goal of the analysis was to measure the polarization of prompt and non-prompt mesons:

- **Unpolarized Scenario:**
  - J/ψ mesons with p_T-independent polarization.
  - Matches existing CMS data.

- **Polarized Scenarios:**
  - Accidental Degeneracy: certain combinations of contributions (${}^3S_1^{[8]} + {}^3P_J^{[8]}$) are indistinguishable from ${}^1S_0^{[8]}$.
  - Current p_T distribution data have not the needed resolving power.

- Polarization measurements over a broader p_T range could resolve ambiguities and identify the contributions from different octet components.

DATA COLLECTED BY CMS (2017-2018)

CENTER-OF-MASS ENERGY: 13 TeV

INTEGRATED LUMINOSITY: 103.3/FB

CMS

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Quarkonia are usually determined by measuring the angular distributions of the positive muons from the decay

$$W(\cos\vartheta, \varphi \mid \vec{\lambda}) = \frac{3}{4\pi(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

In the helicity frame and integrating over phi we get a more friendly observable:

$$W(\cos\vartheta_{\mathrm{HX}}) \propto 1 + \lambda_\vartheta^{\mathrm{HX}} \cos^2\vartheta_{\mathrm{HX}}$$

J/ψ and ψ (2S)

NPS = non prompt - PRS = prompt

CLICK ME

- **Measured Parameter:**
  - Polar anisotropy λ_θ using $|\cos\vartheta_{HX}|$ distributions.
- **Contributions Considered:**
  - Decays from B-mesons.
  - Non-prompt continuum background (CNP).
  - Prompt (CPR).
- **Fraction Estimation:**
  - Determined from dimuon mass distributions and decay lengths.
  - Provides insights into production mechanisms and polarization dependencies.

The contribution in the prompt region can be described with :

$$\mathrm{PRS}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}) = f^{\mathrm{PRS}}_{\psi_{\mathrm{P}}}(p_{\mathrm{T}})\,\psi_{\mathrm{P}}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}) + f^{\mathrm{PRS}}_{\mathrm{C_{PR}}}(p_{\mathrm{T}})\,\mathrm{C_{PR}}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}) + f^{\mathrm{PRS}}_{\psi_{\mathrm{B}}}(p_{\mathrm{T}})\,\psi_{\mathrm{B}}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}).$$

In the non-prompt region it can be described with :

$$\mathrm{NPS}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}) = f^{\mathrm{NPS}}_{\psi_{\mathrm{B}}}(p_{\mathrm{T}})\,\psi_{\mathrm{B}}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}) + f^{\mathrm{NPS}}_{\mathrm{C_{NP}}}(p_{\mathrm{T}})\,\mathrm{C_{NP}}(|\cos\vartheta_{\mathrm{HX}}|, p_{\mathrm{T}}).$$

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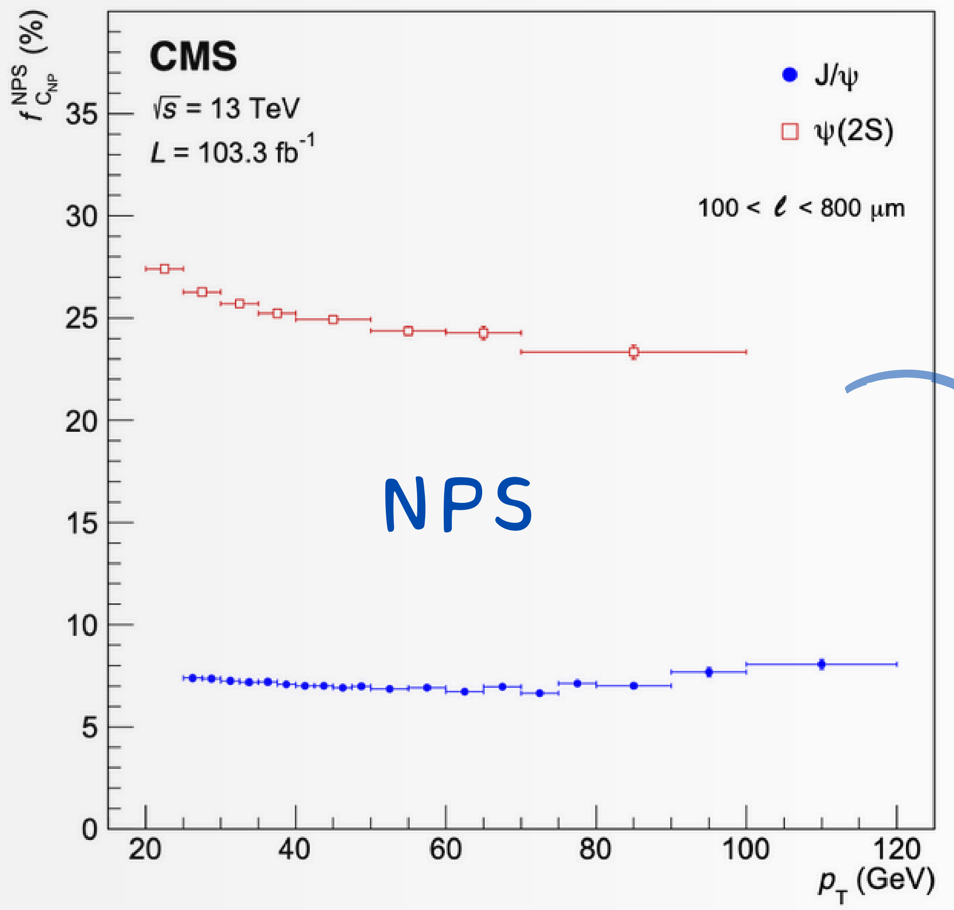


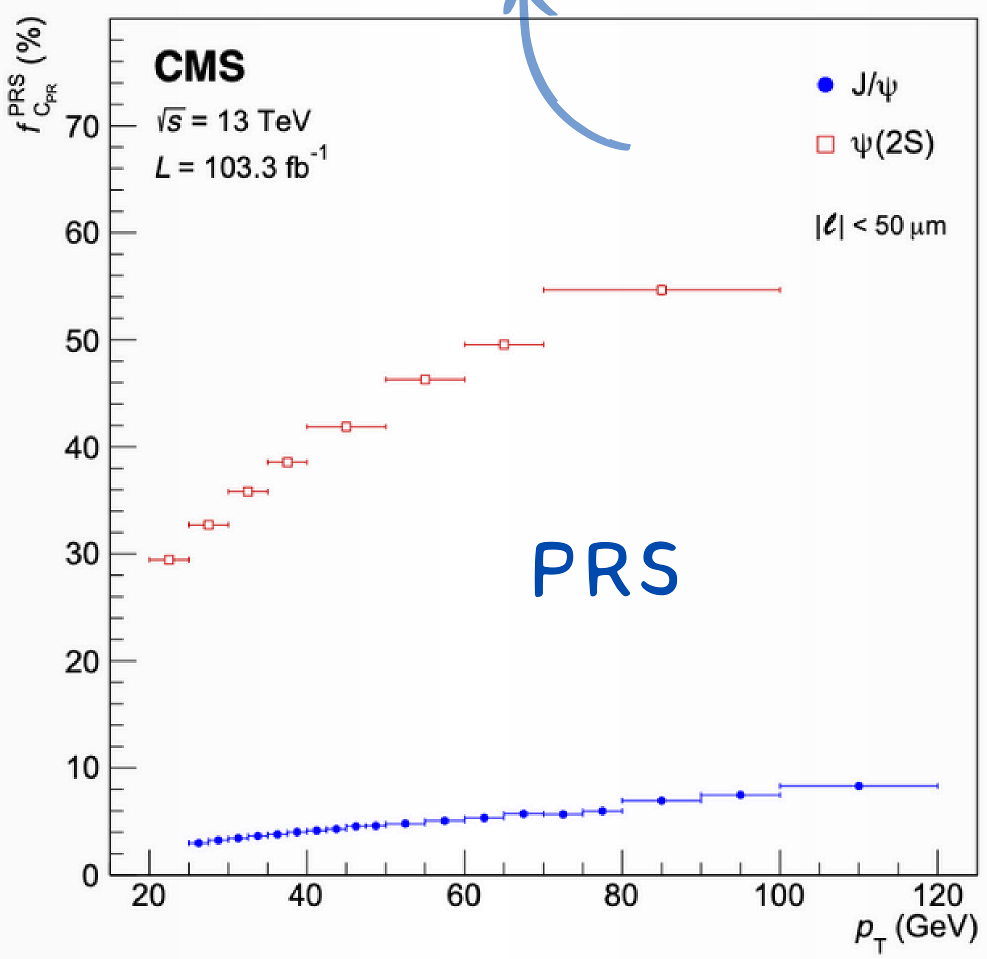
CLICK ME

The fractions of continuum muon pairs in the signal windows are determined from fits to the dimuon mass distributions

The contribution in the prompt region can be described with :

$$\mathrm{PRS}(|\cos\vartheta_{HX}|, p_T) = f^{\mathrm{PRS}}_{\psi_P}(p_T)\,\psi_P(|\cos\vartheta_{HX}|, p_T) + f^{\mathrm{PRS}}_{C_{PR}}(p_T)\,C_{PR}(|\cos\vartheta_{HX}|, p_T) + f^{\mathrm{PRS}}_{\psi_B}(p_T)\,\psi_B(|\cos\vartheta_{HX}|, p_T).$$

The fractions of charmonia from B meson decays are obtained by fitting the dimuon decay length distributions



In the non-prompt region it can be described with :

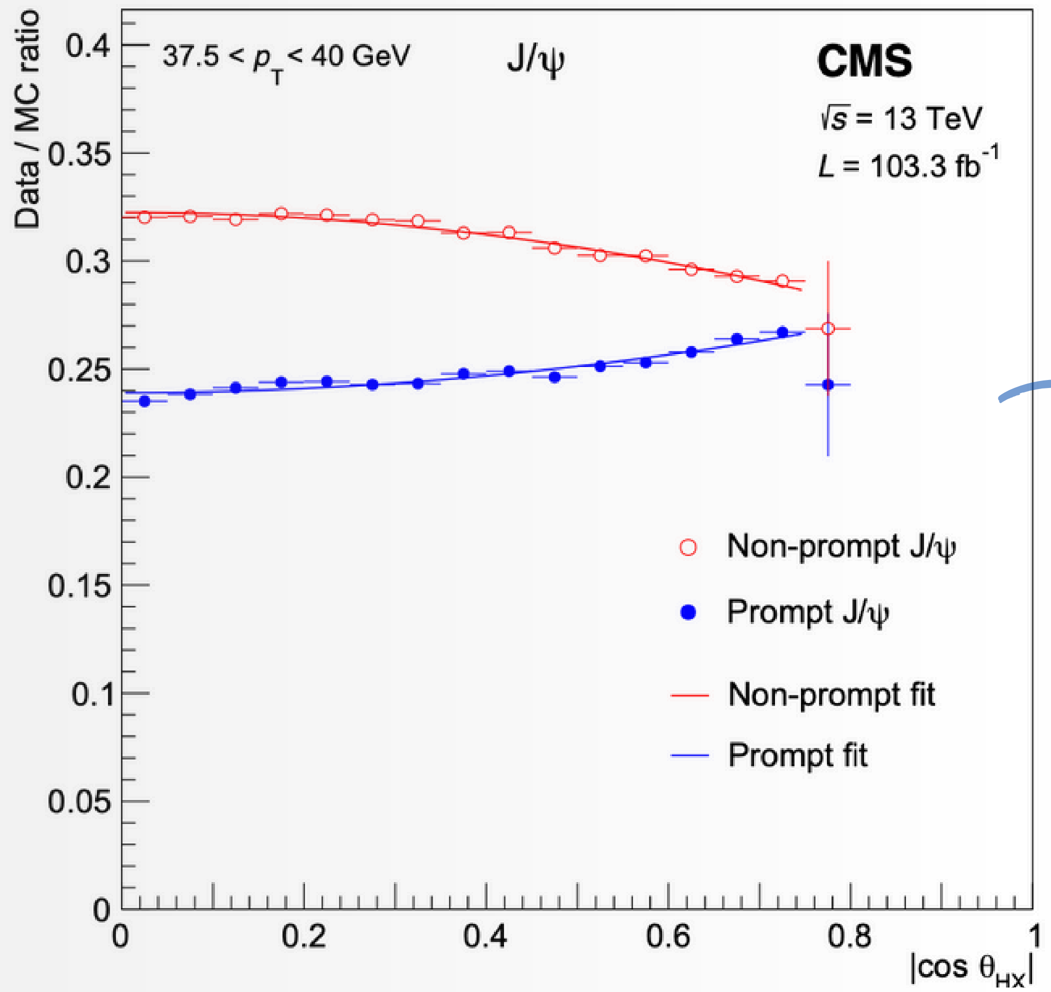
$$\mathrm{NPS}(|\cos\vartheta_{HX}|, p_T) = f^{\mathrm{NPS}}_{\psi_B}(p_T)\,\psi_B(|\cos\vartheta_{HX}|, p_T) + f^{\mathrm{NPS}}_{C_{NP}}(p_T)\,C_{NP}(|\cos\vartheta_{HX}|, p_T).$$

J/ψ and ψ (2S)

For each p_T bin:

- The PRS and NPS $|\cos\vartheta_{\mathrm{HX}}|$ distributions are **extracted directly from the data.**
- Continuum **background distributions are determined as weighted averages** of events in the low and high mass sidebands.
- Weights are calculated by integrating the fitted dimuon mass background function within the sideband regions, which are largely p_T-independent and approximately 50% for both states.

$|\cos\vartheta_{\mathrm{HX}}|$ distributions are obtained, for each p_T bin, by subtracting from the NPS sample the non-prompt mass continuum background and scaled by the background fractions.

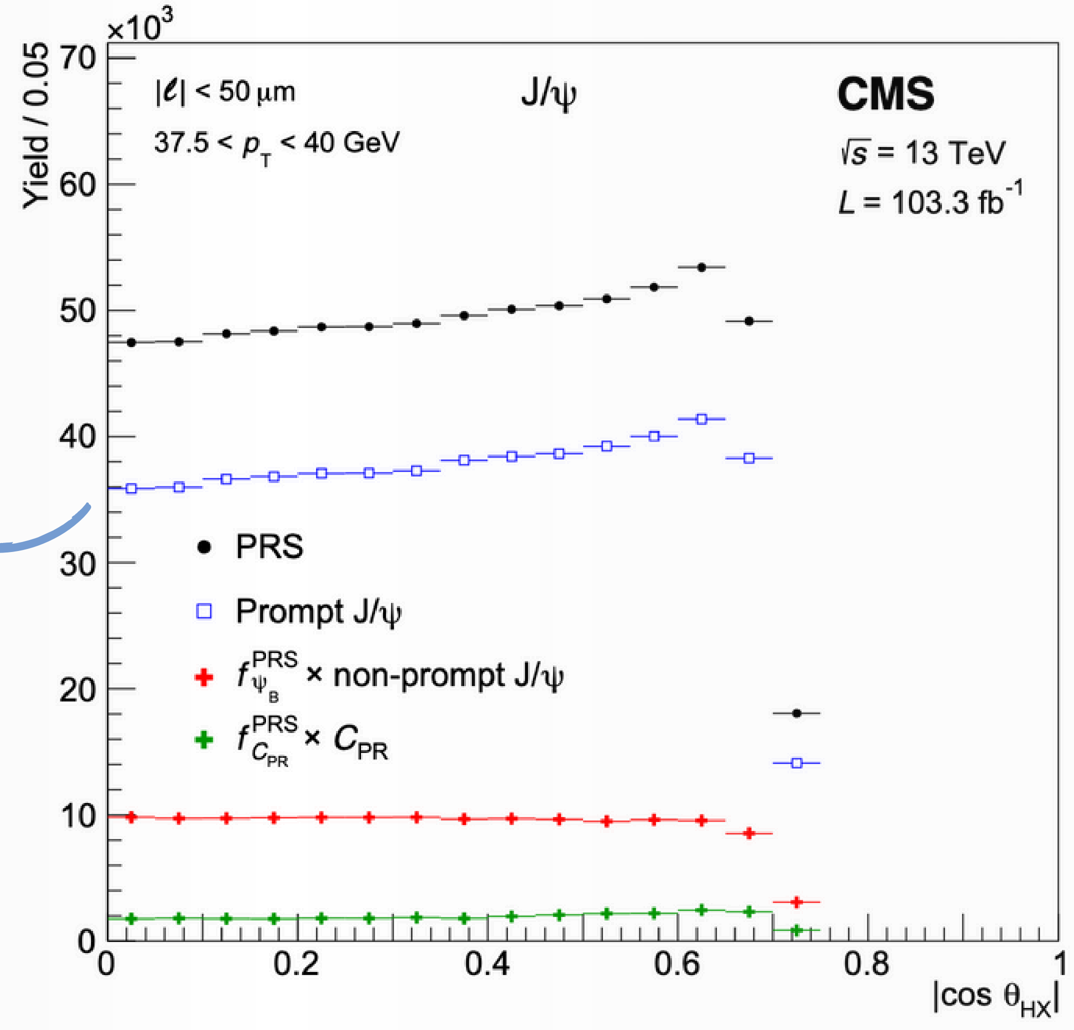


CLICK ME

MC comparison

J/ψ

Cosine yields in p_T bins



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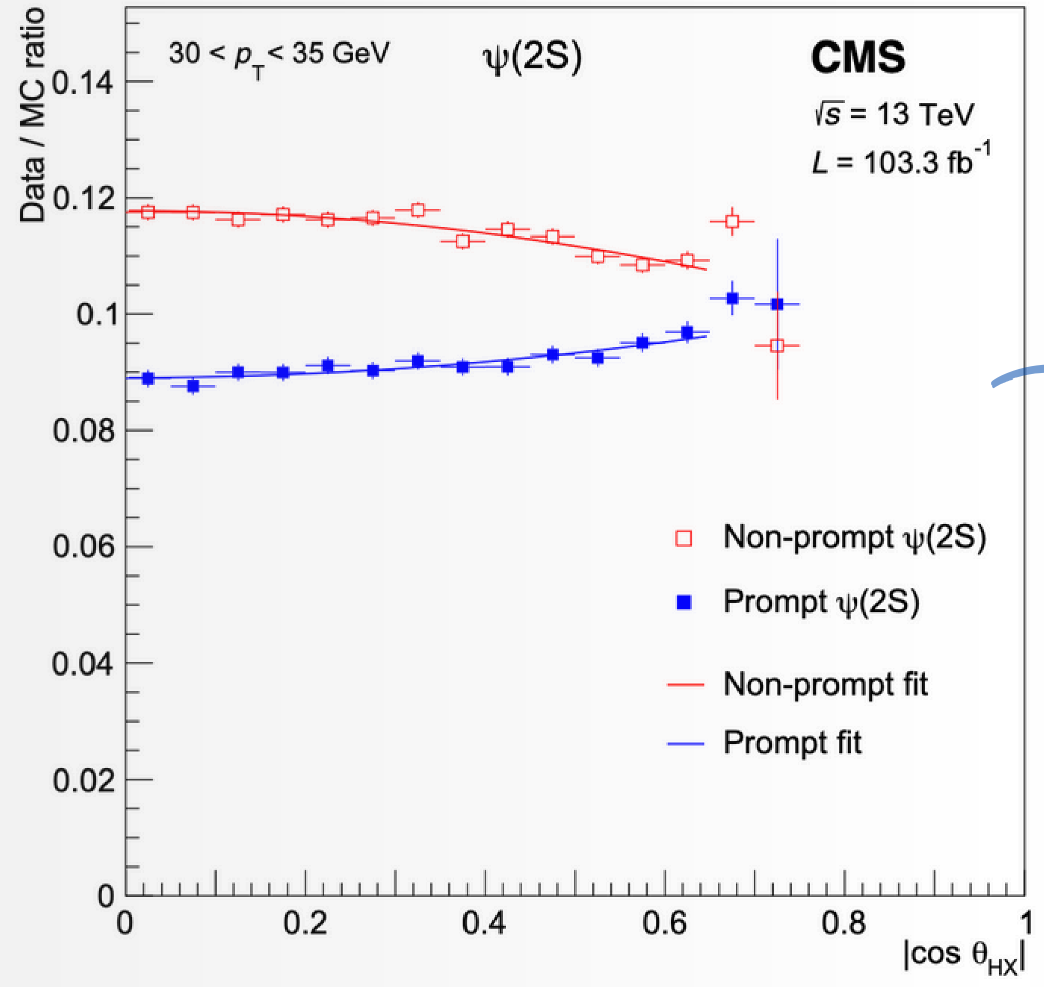

CLICK ME

MC comparison

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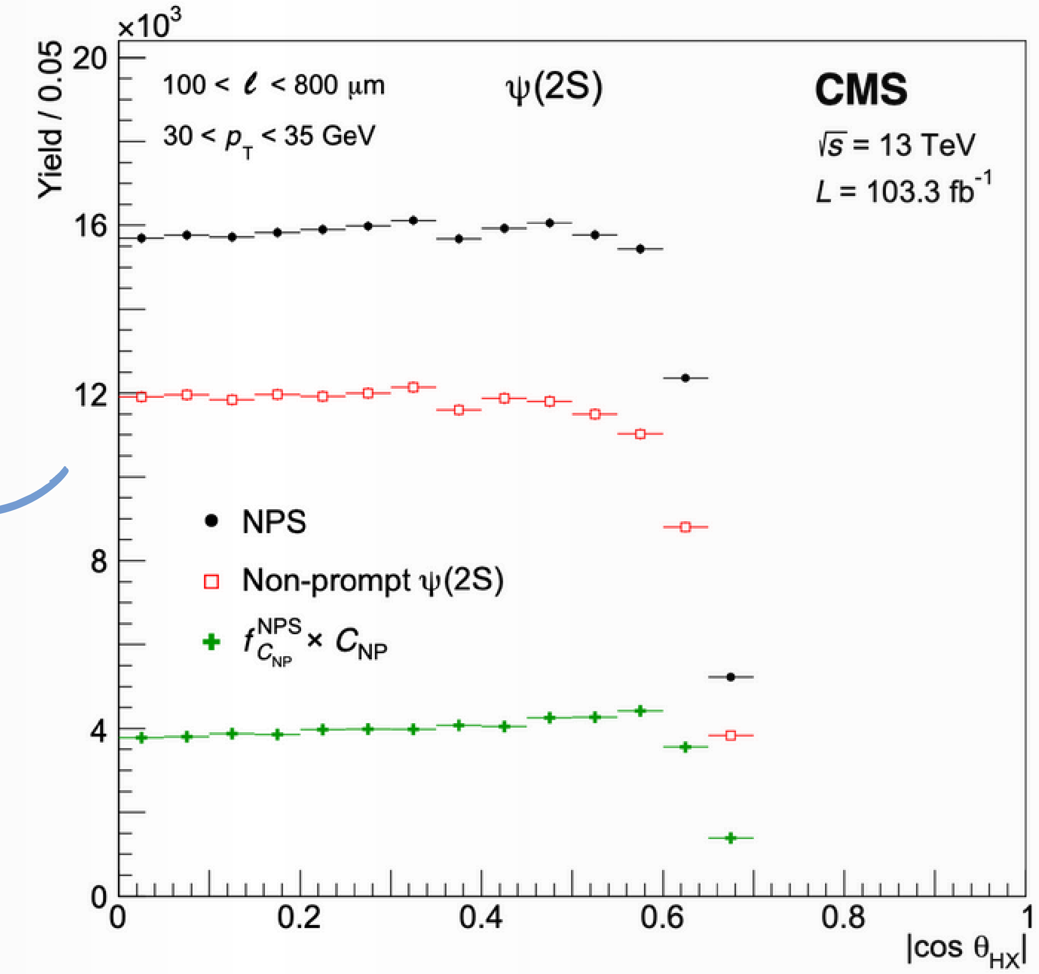
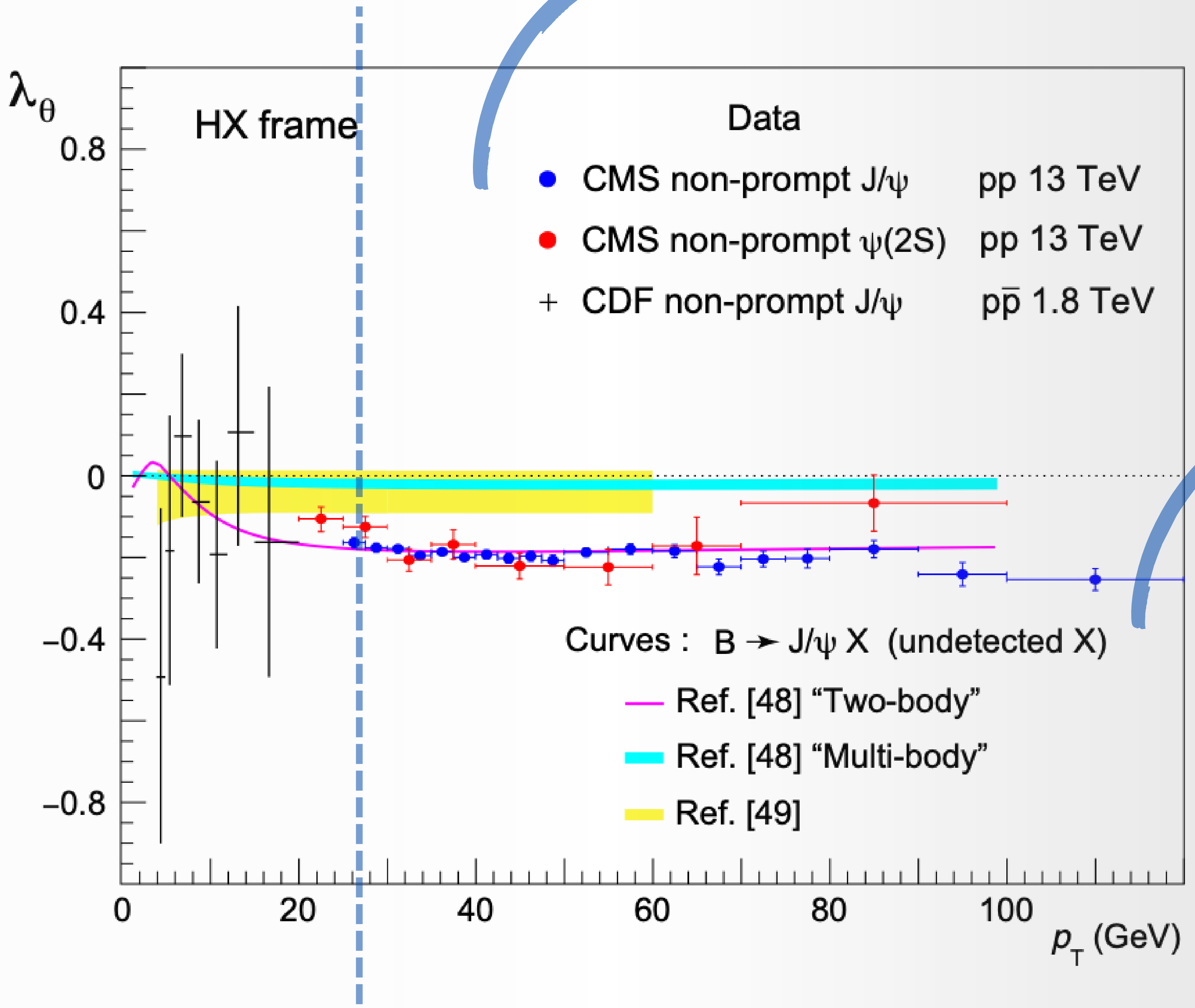


J/ψ and ψ (2S)

the measured values show a flat dependence with a plateaux at -0.2



NON PROMPT

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"two-body", X is a kaon or another J= 0 meson with similar or smaller mass

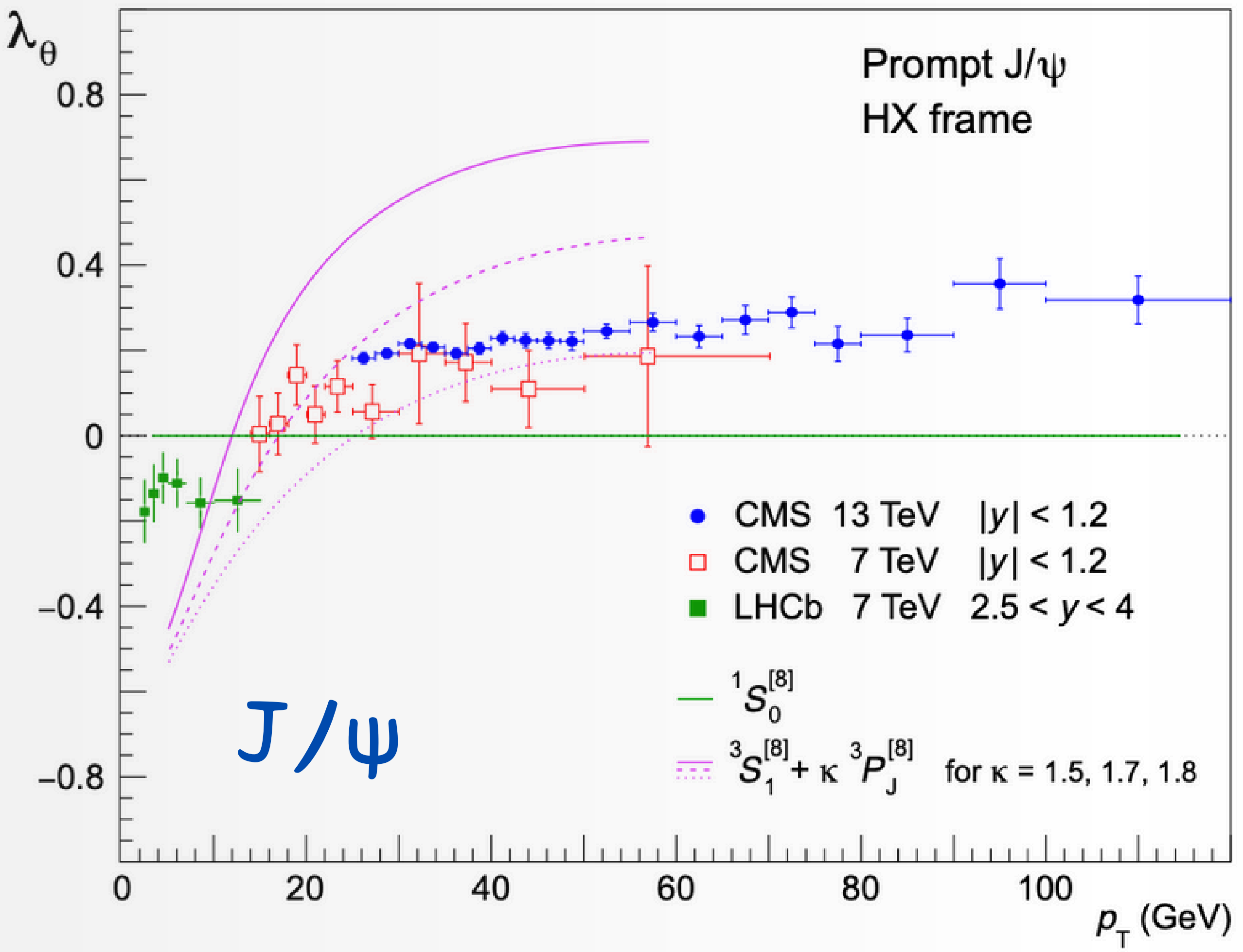
"multi-body", collectively considers all other systems of accompanying particles (including single particles of J= 1)

Non-prompt J/ψ production (at least for p_T > 25 GeV) is dominated by the "two-body" topology, where the J/ψ is expected to be predominantly produced through colour-singlet processes

J/ψ and ψ (2S)

PROMPT

- Measured p_T-dependence are compared with predictions from the three dominant NRQCD color-octet terms:
  - ${}^1S_0^{[8]}$: unpolarized
  - ${}^3S_1^{[8]} + \kappa\ {}^3P_J^{[8]}$: polarized, transitioning from longitudinal to transverse around a threshold determined by κ.
- Transition point in λ_ϑ constrains κ
- High-p_T asymptotes constrain relative weights of polarized vs. unpolarized terms.



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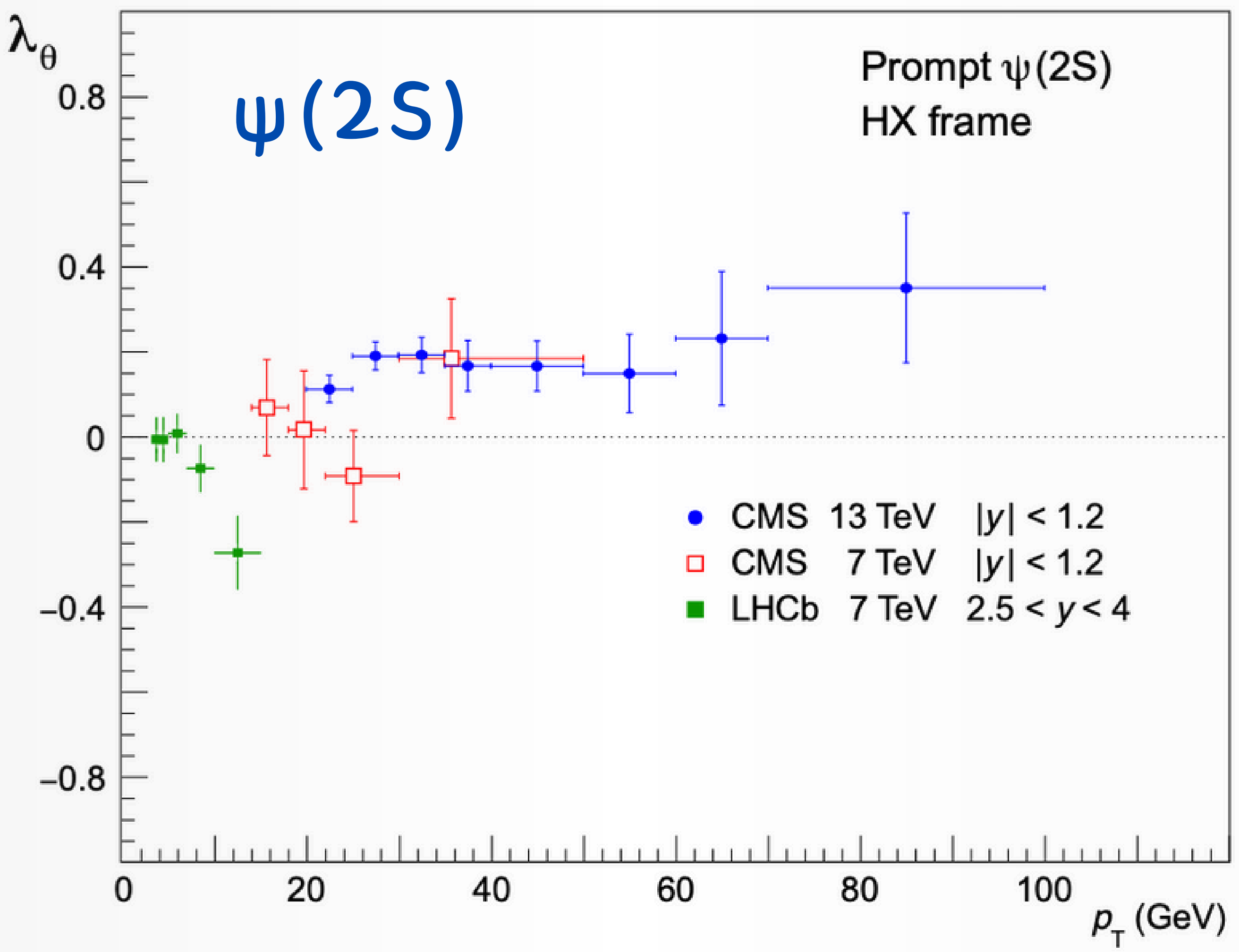

J/ψ and ψ (2S)

ATLAS has previously **measured the inclusive differential cross-section** for J/ψ and ψ(2S) production in pp collisions at √s = 7 and 8 TeV .

The new kinematic region is 8-360 GeV for the J/ψ and 8-140 GeV for the ψ(2S) which allowed the use of two separate triggers.

The measurements include:

- the **double-differential cross-sections** for production of the two vector charmonium states

DATA COLLECTED BY ATLAS (2015-2018)

CENTER-OF-MASS ENERGY: 13 TeV

INTEGRATED LUMINOSITY: 140/FB

ATLAS EXPERIMENT

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$$\frac{d^2\sigma^{P,NP}(pp \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{trig}\epsilon_{trigSF}\epsilon_{reco}\epsilon_{recoSF}} \frac{N_\psi^{P,NP}}{\Delta p_T \, \Delta y \, \int \mathcal{L}dt}$$

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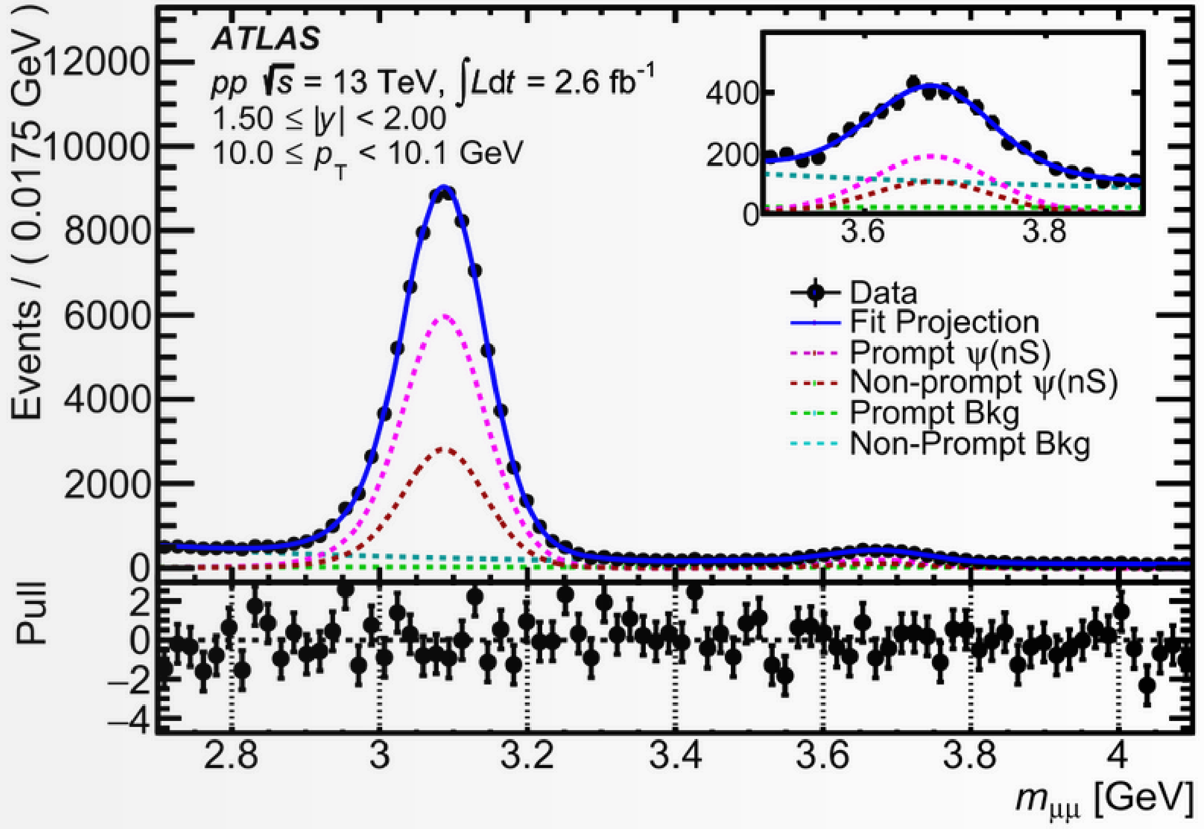
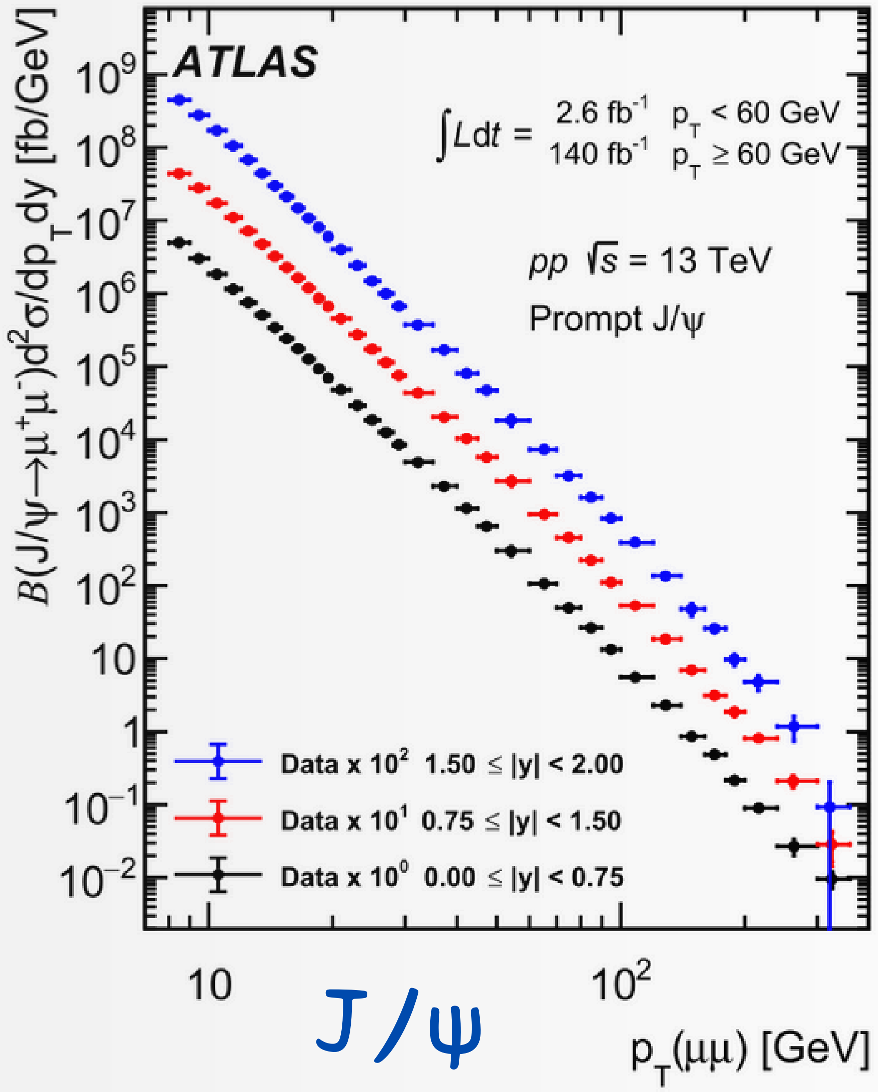
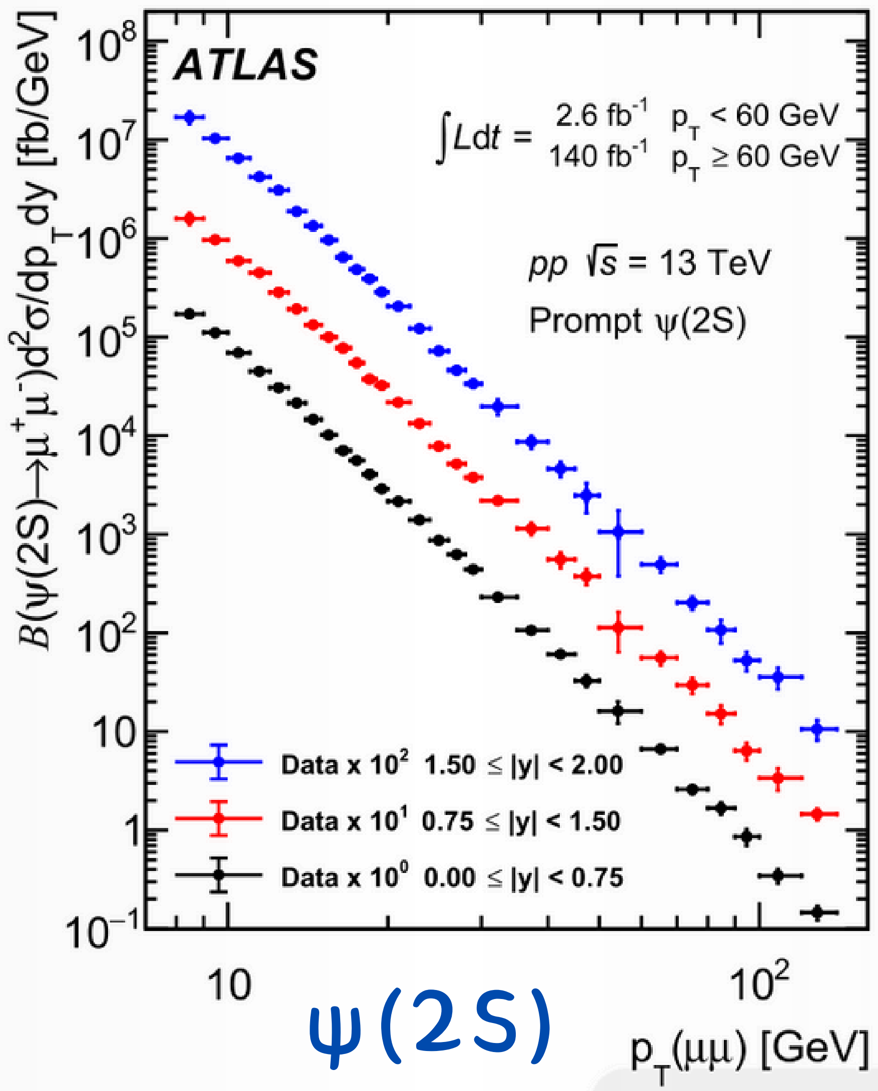




J/ψ



ψ(2S)

CLICK ME

J/ψ and ψ (2S)

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$$\frac{\mathrm{d}^2\sigma^{\mathrm{P,NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{\mathrm{trig}}\epsilon_{\mathrm{trigSF}}\epsilon_{\mathrm{reco}}\epsilon_{\mathrm{recoSF}}} \frac{N_{\psi}^{\mathrm{P,NP}}}{\Delta p_{\mathrm{T}}\ \Delta y\ \int \mathcal{L}\mathrm{d}t}$$

$$F_{\psi}^{\mathrm{NP}}(p_{\mathrm{T}}, y) = \frac{\mathrm{d}^2\sigma^{\mathrm{NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \left[\frac{\mathrm{d}^2\sigma^{\mathrm{P}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} + \frac{\mathrm{d}^2\sigma^{\mathrm{NP}}(pp \to \psi)}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right]^{-1}$$

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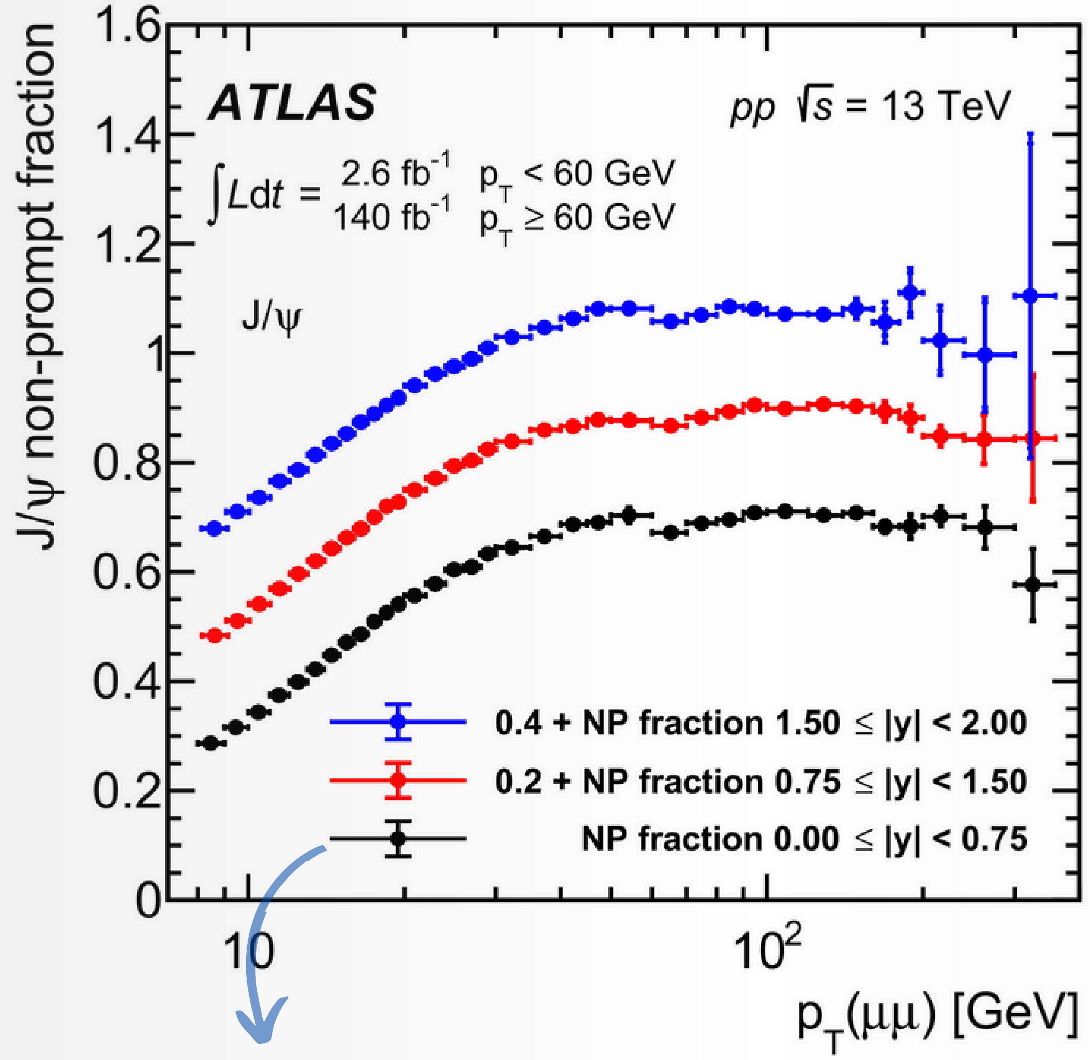
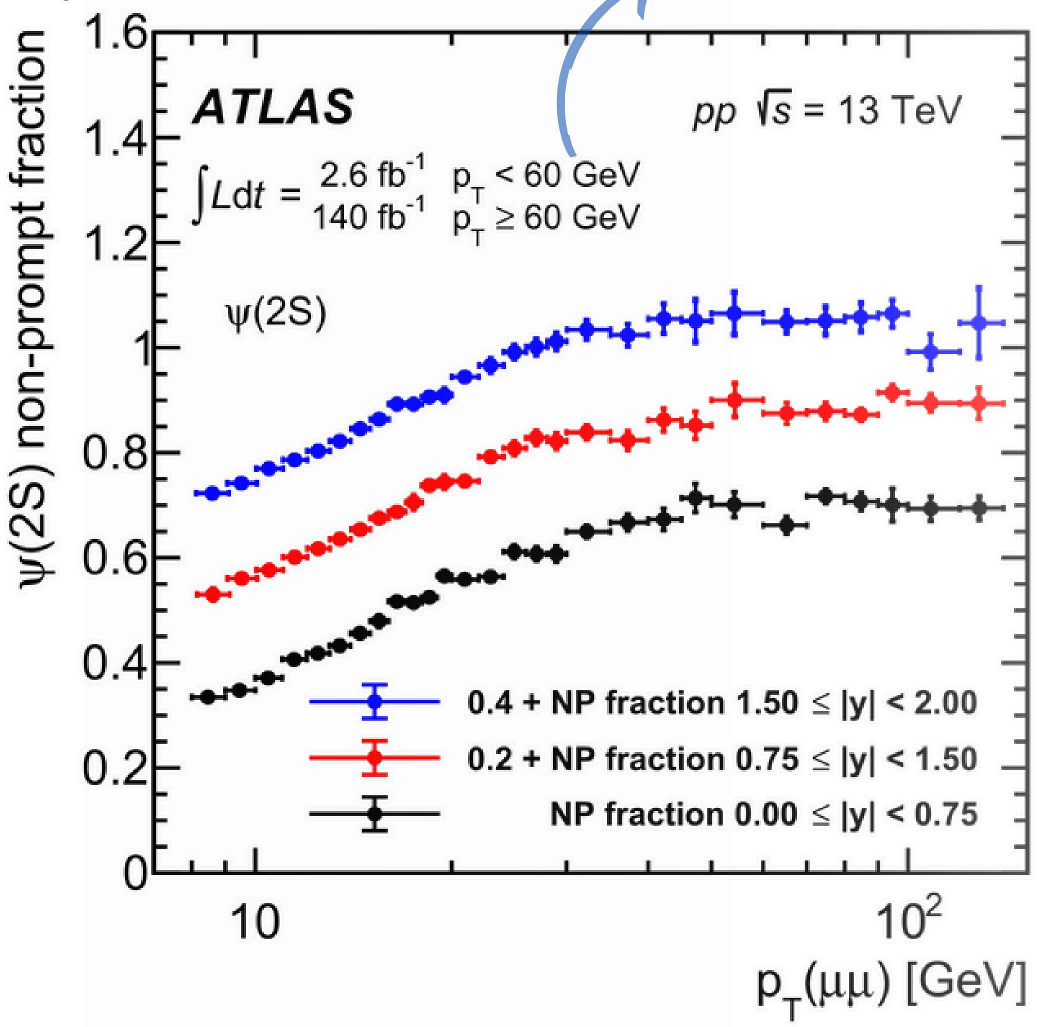


J/ψ

CLICK ME

ψ(2S)



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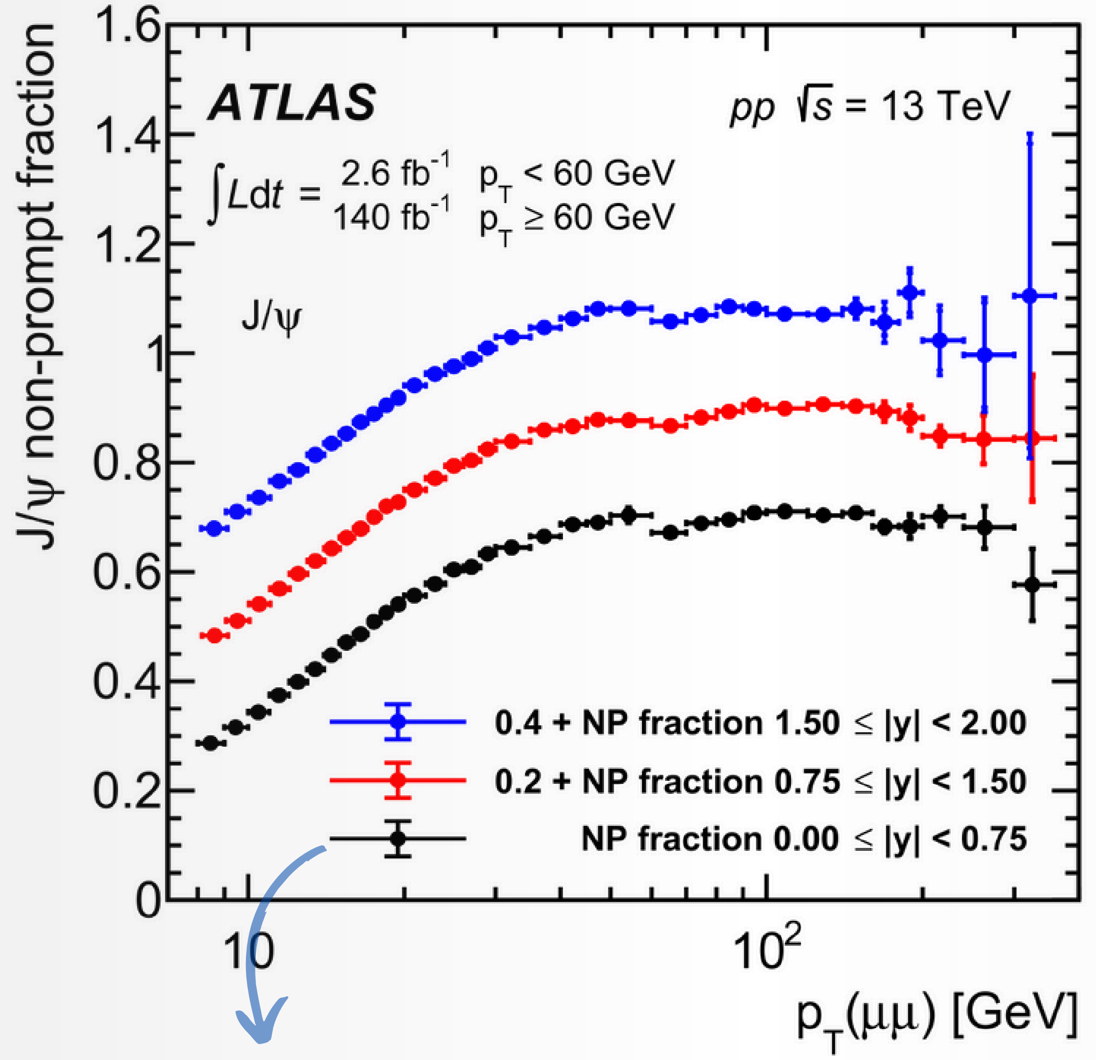
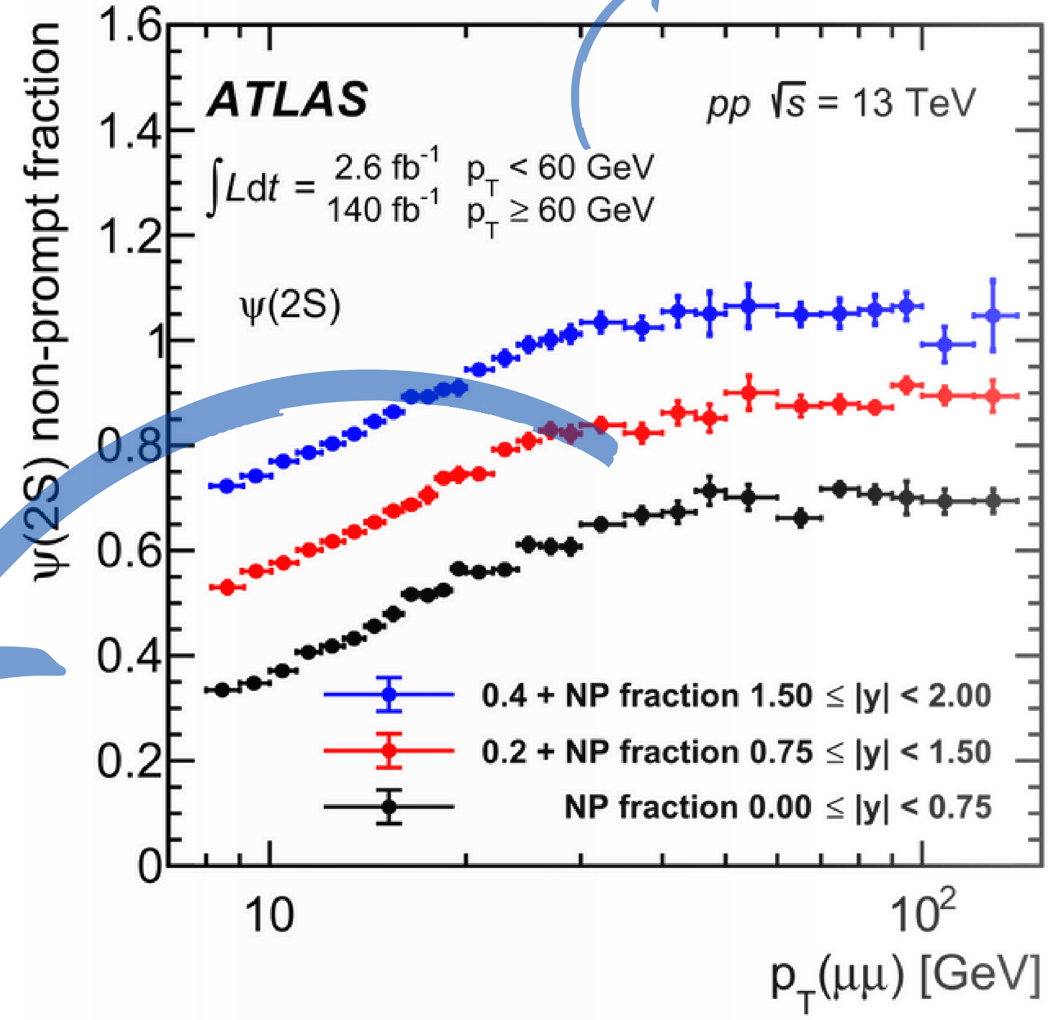


J/ψ

ATLAS EXPERIMENT

CLICK ME

ψ(2S)



The non-prompt fractions with pT up to about 100 GeV, they are almost constant for both J/ψ and ψ(2S) in the high p_T range, which suggests similar p_T-dependences

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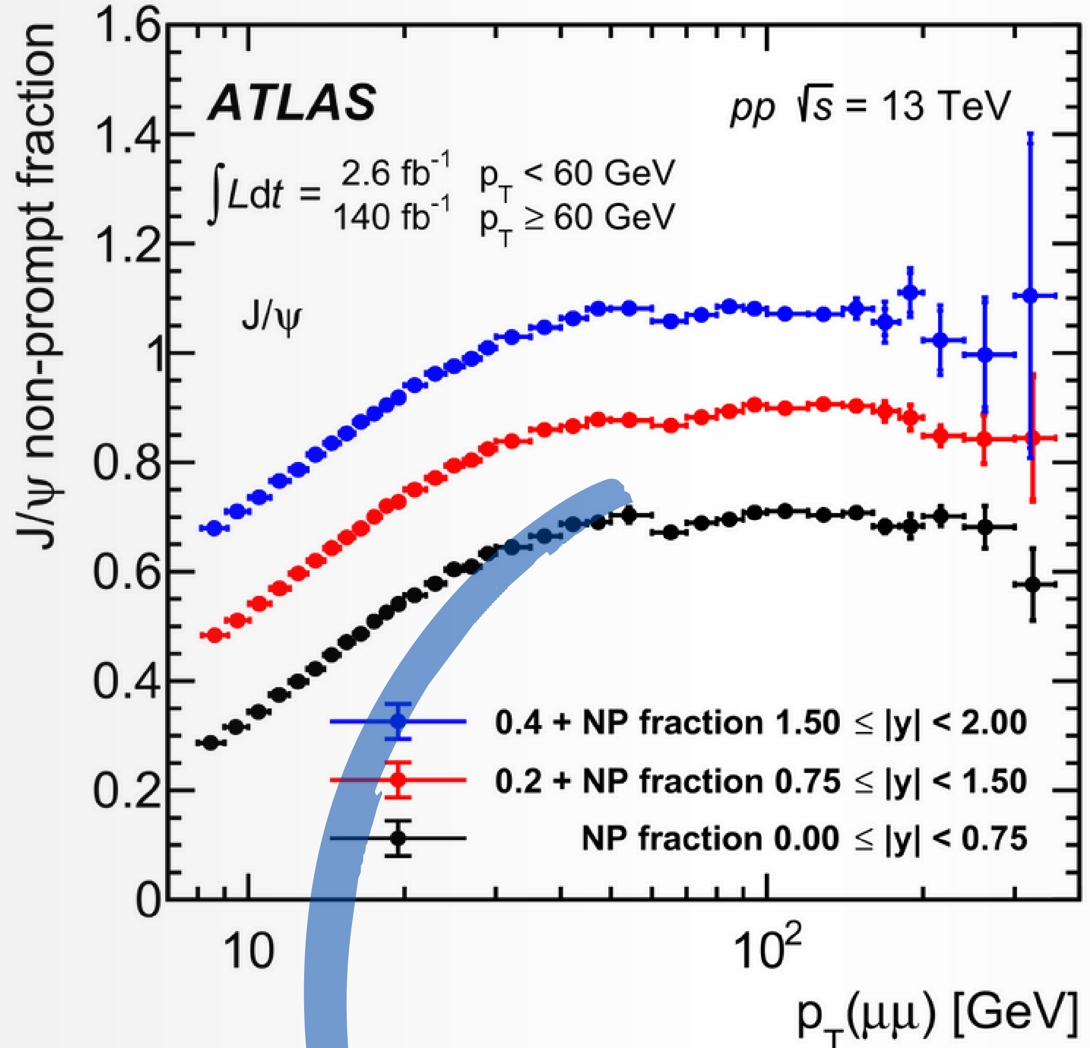
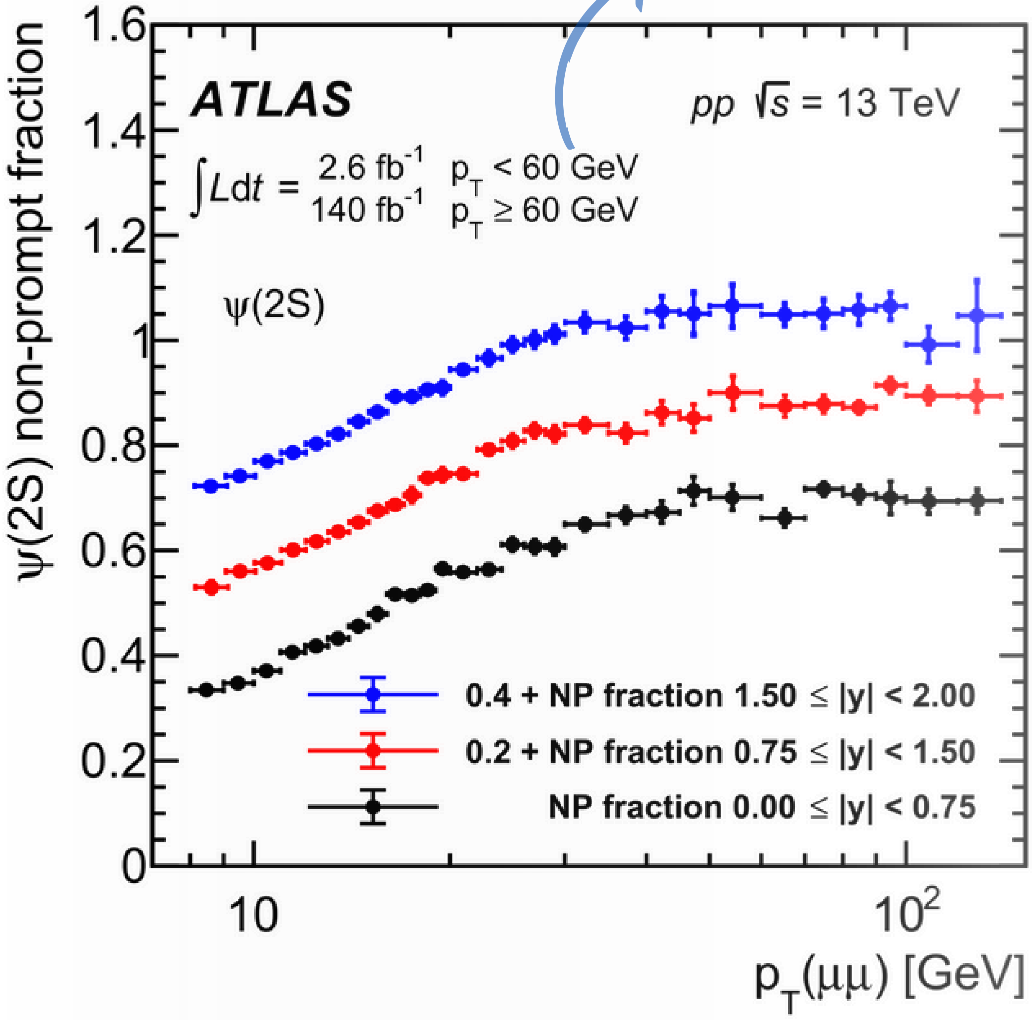


CLICK ME

potential bias due to the spin-alignment assumption reflecting a possible issue in the spin-alignment modelling.

ψ(2S)



J/ψ and ψ (2S)

DATA COLLECTED BY ATLAS (2015-2018)
CENTER-OF-MASS ENERGY: 13 TeV
INTEGRATED LUMINOSITY: 140/FB

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CLICK ME

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- the prompt and non-prompt **ψ(2S)-to-J/ψ production ratios**

$$\frac{d^2\sigma^{P,NP}(pp \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{trig}\epsilon_{trigSF}\epsilon_{reco}\epsilon_{recoSF}} \frac{N_\psi^{P,NP}}{\Delta p_T \, \Delta y \, \int \mathcal{L} dt}$$

$$F_\psi^{NP}(p_T, y) = \frac{d^2\sigma^{NP}(pp \to \psi)}{dp_T dy} \times \left[\frac{d^2\sigma^{P}(pp \to \psi)}{dp_T dy} + \frac{d^2\sigma^{NP}(pp \to \psi)}{dp_T dy}\right]^{-1}$$

$$R^{P,NP}(p_T, y) = \frac{d^2\sigma^{P,NP}(pp \to \psi(2S))}{dp_T dy} \times \mathcal{B}(\psi(2S) \to \mu^+\mu^-) \times \left[\frac{d^2\sigma^{P,NP}(pp \to J/\psi)}{dp_T dy} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]^{-1}$$

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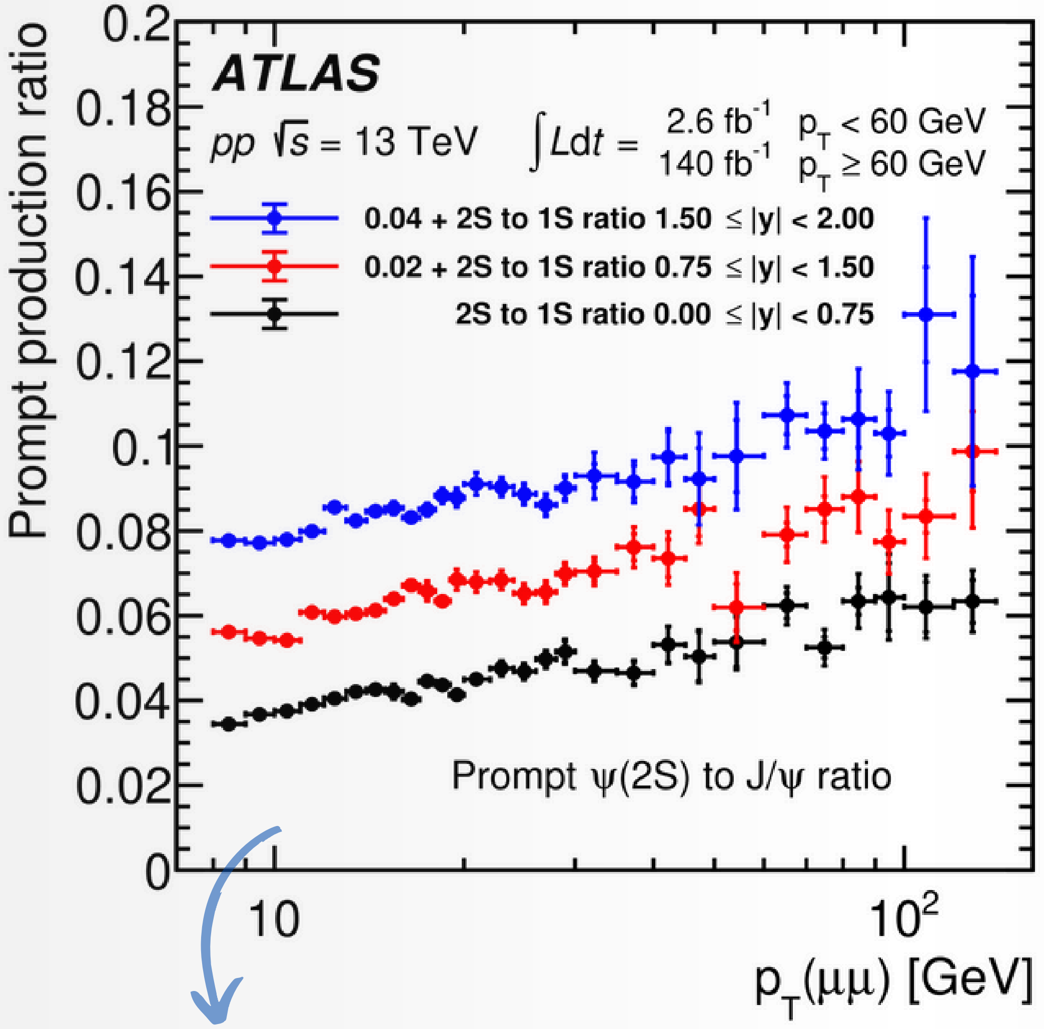
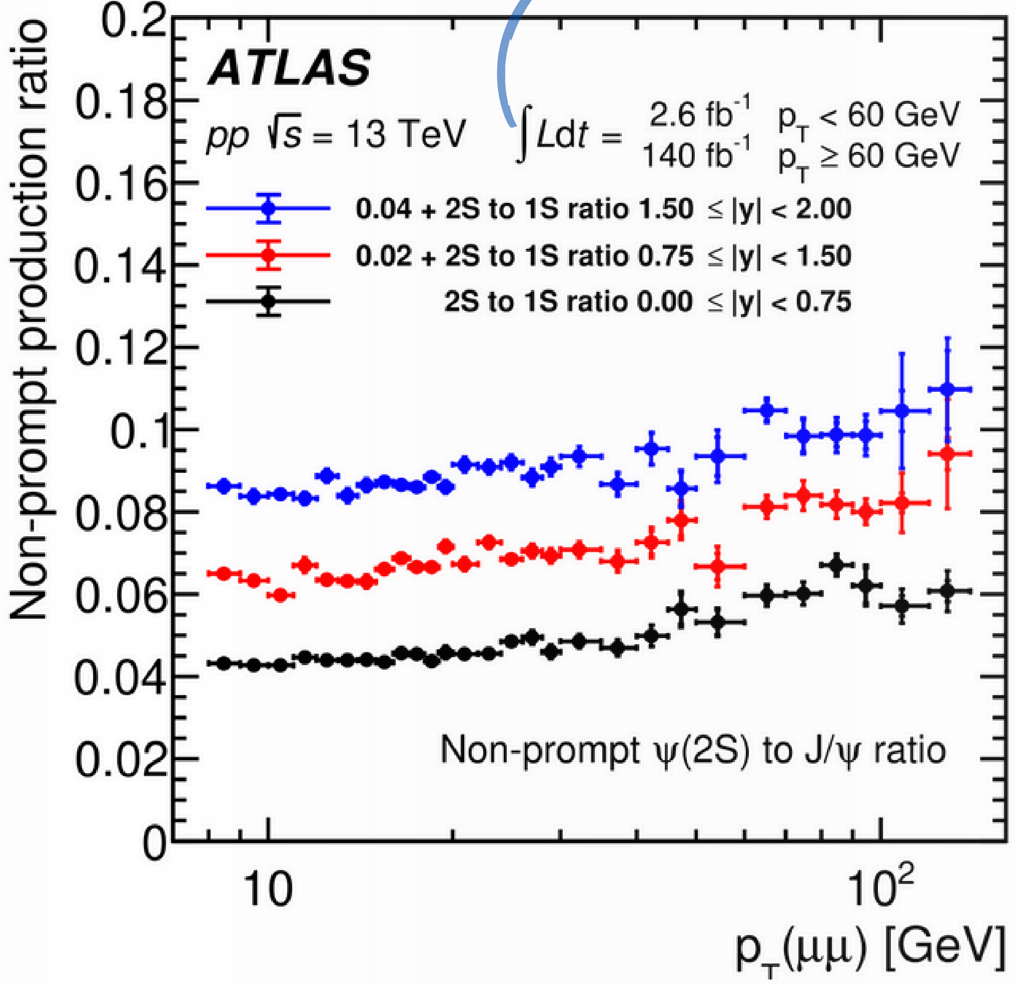


Prompt

Non-Prompt

CLICK ME



J/ψ AND ψ(2S)

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THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

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CERN, 1211 Geneva 23, Switzerland

Received: 4 October 2023 / Accepted: 12 January 2024

CMS

CERN-EP-2024-155
2024/06/21

CMS-BPH-22-009

Measurement of the polarizations of prompt and non-prompt J/ψ and ψ(2S) mesons produced in pp collisions at $\sqrt{s} = 13$ TeV

J/ψ IN 4 MUONS

CMS

CERN-EP-2024-058
2024/06/10

CMS-BPH-22-006

Observation of the J/$\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

CONF-2024-001
April 2, 2024

Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

J/ψ in 4-mu

- **Large electromagnetic** decay width compared to its strong decay width for the **OZI rule**.
- Excellent tool for probing **rare electromagnetic processes** and the theory of QED.

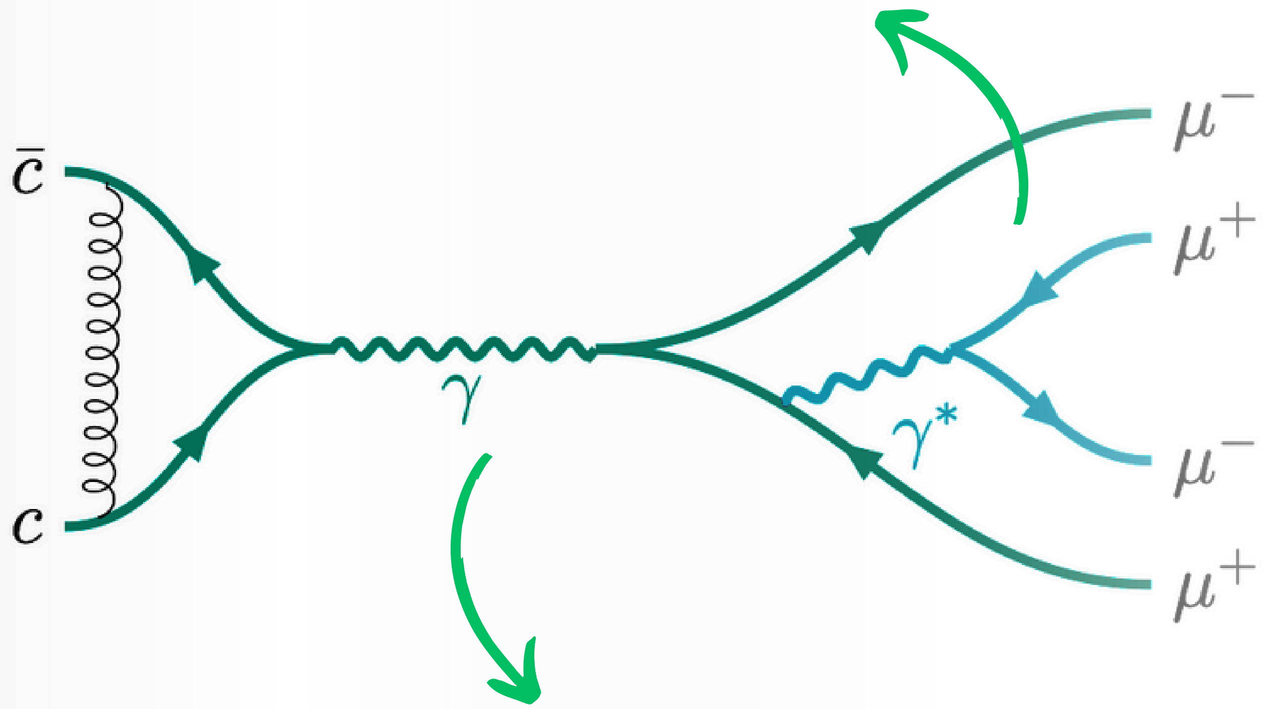
- **PRO:** large production cross-sections of vector quarkonia and easy to reconstruct and identify
- **CONS:** huge hadronic backgrounds

Assuming that the **SM rate is dominated by the FSR process**, it is possible to **separate the hadronic physics of the J/ψ annihilation into a virtual photon** (identical for 4 and 2 muons decays), **and the electromagnetic process of FSR** (only appearing in the 4 muons)

DATA COLLECTED BY CMS (2018)
CENTER-OF-MASS ENERGY: 13 TeV
INTEGRATED LUMINOSITY: 33.6/FB

CLICK ME

final-state radiation (FSR) of a virtual photon (γ*)



processes like $J/\psi \to VV \to \mu^+\mu^-\mu^+\mu^-$ are forbidden by C-parity conservation

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$$R_{\mathcal{B}} \equiv \mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)/\mathcal{B}(J/\psi \to \mu^+\mu^-).$$

(This observable is convenient because it allows the cancellation of numerous sources of systematic uncertainties)

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CMS

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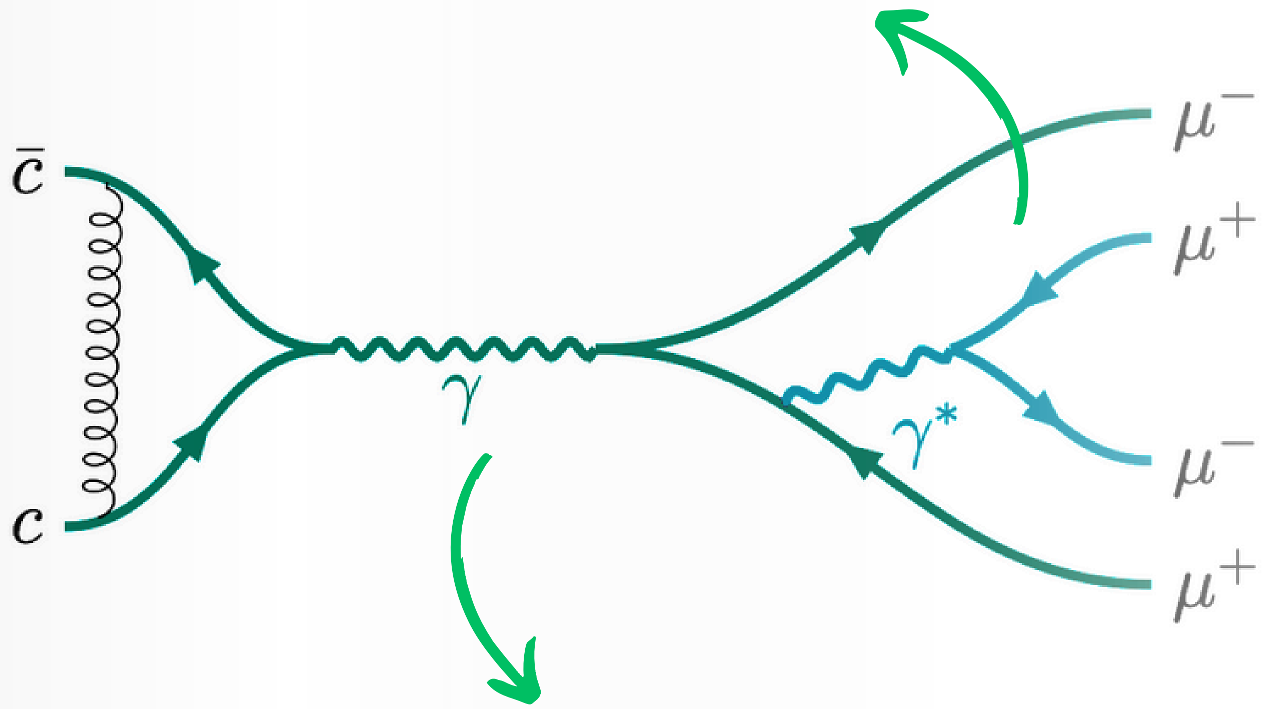

processes like J/ψ→VV→μ+μ−μ+μ− are forbidden by C-parity conservation

J/ψ in 4-mu

DATA COLLECTED BY CMS (2018)
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INTEGRATED LUMINOSITY: 33.6/FB

CMS
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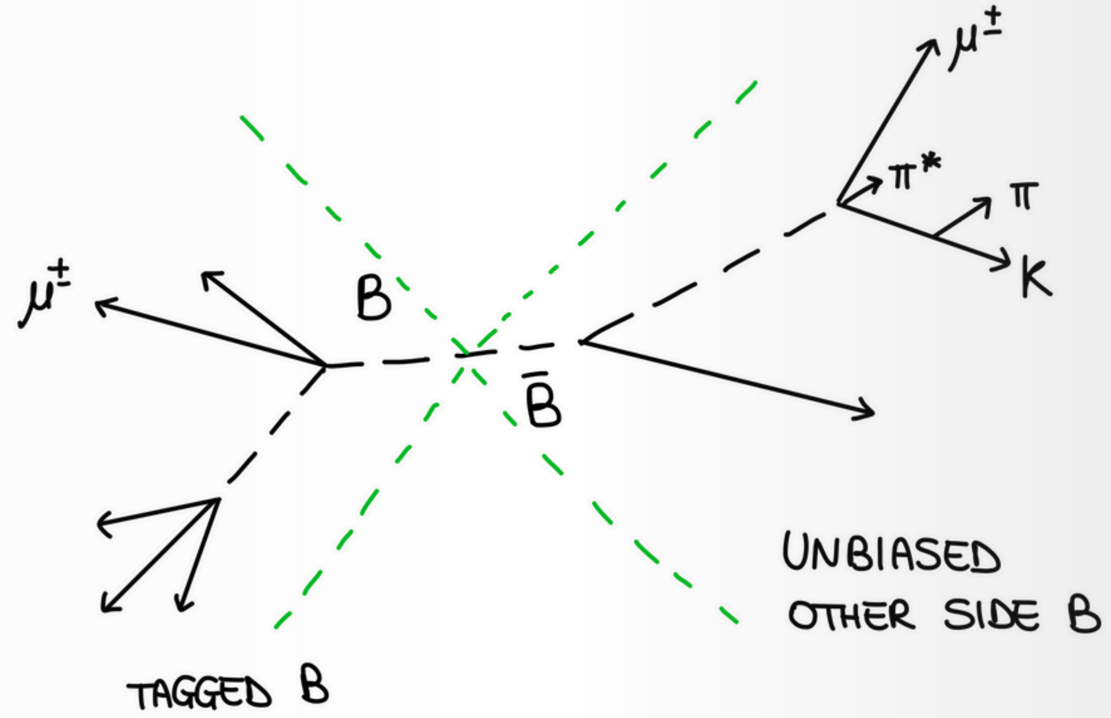
Candidate selection:

- **B Parking data sample*** has been used;
- Each muon with $p_T > 3.4$ GeV/c with $|\eta| < 1.5$;
- The regions of known di-muon resonance are excluded;

*A specialized lumi-dependent trigger and data storage strategy was implemented to assemble a data set enriched in b hadron decays



$$R_{\mathcal{B}} \equiv \mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)/\mathcal{B}(J/\psi \to \mu^+\mu^-).$$

and was measured to be:

$$\frac{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)} = [16.9^{+5.5}_{-4.6}\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})] \times 10^{-6}$$

Saturate bandwidth with Bs when standard physics stream rate drops

J/ψ in 4-mu

$$\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{N(J/\psi \to \mu^+\mu^-)} \Big/ \frac{\epsilon_{J/\psi\to\mu^+\mu^-\mu^+\mu^-}}{\epsilon_{J/\psi\to\mu^+\mu^-}}$$

where:

$$(11.92 \pm 0.02)\%$$

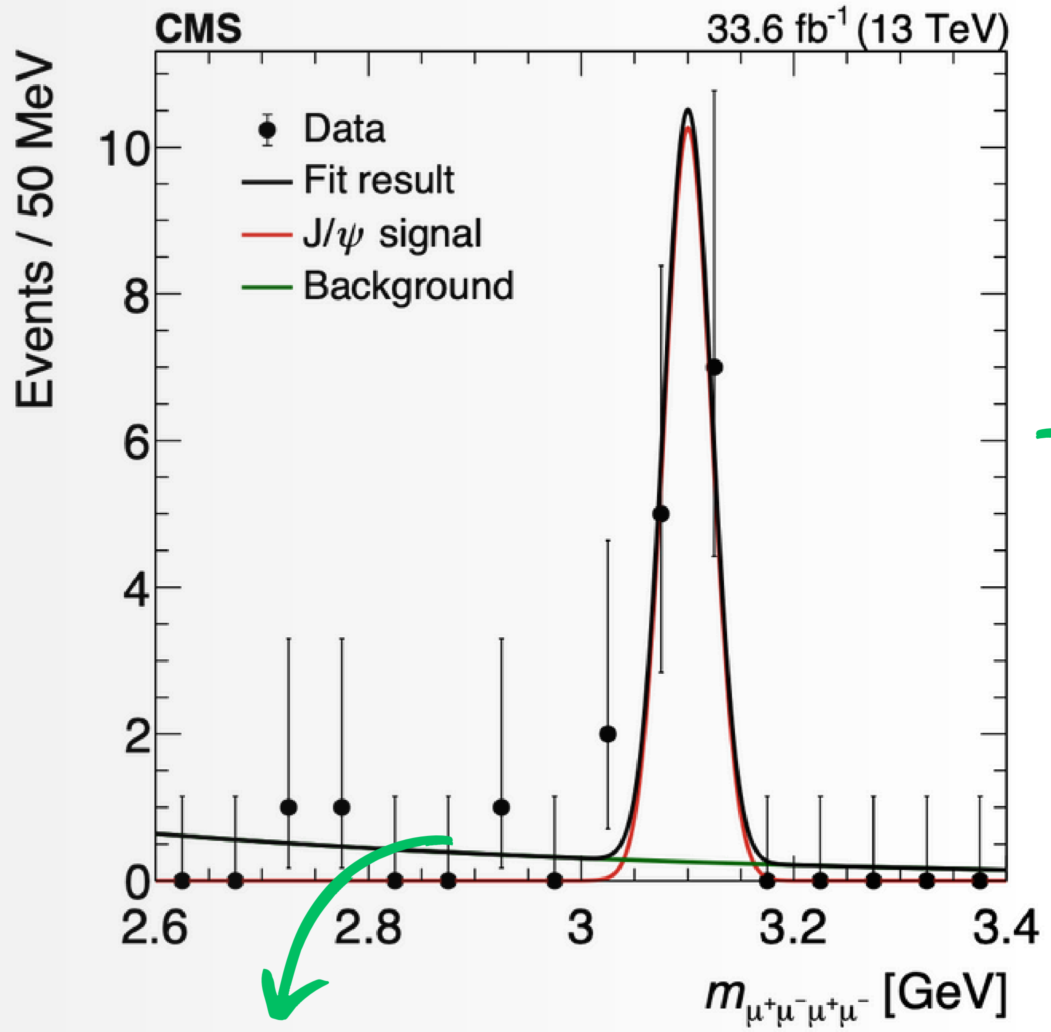
$$N(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = 11.6^{+3.8}_{-3.1}$$

The significance of the signal is above 7 standard deviations, evaluated from the likelihood ratio of the default signal+bkg fit and the bkg-only fit

$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}\,(\text{stat}) \pm 0.4\,(\text{syst})] \times 10^{-7}$$

Standard Model prediction:

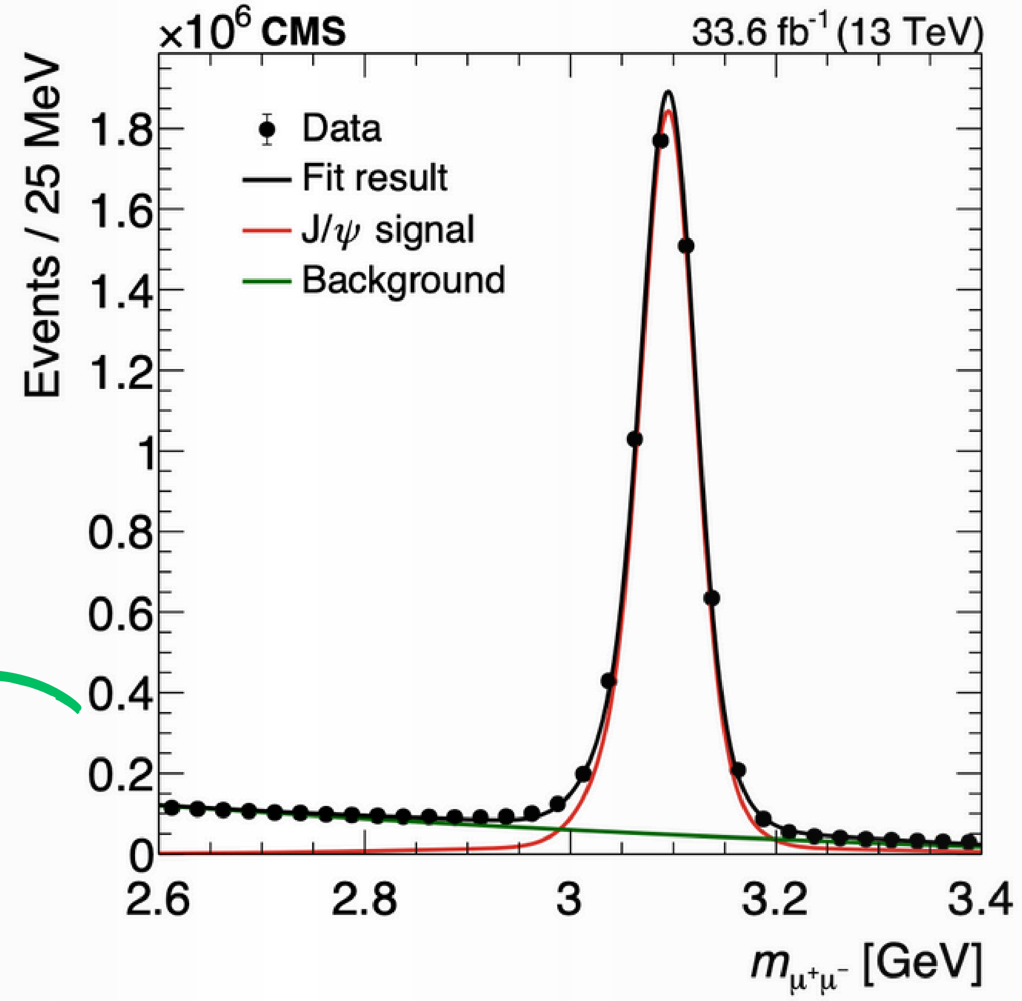
$$(9.74 \pm 0.05) \times 10^{-7}$$



CLICK ME

CrystalBall + Gaussian

$$N = 11.6^{+3.8}_{-3.1}$$



$$N = (5770 \pm 3) \times 10^3$$

J/ψ in 4-mu

$$\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N(J/\psi \to \mu^+ \ldots}{N(J/\psi \to \ldots}$$

where:

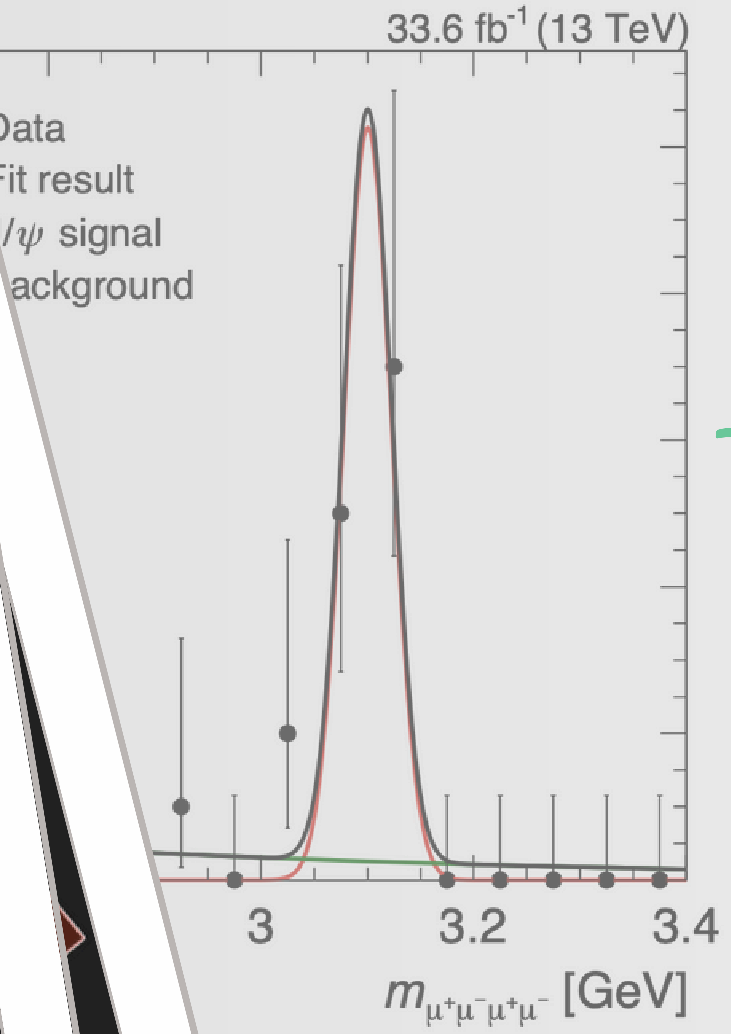
$$N(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = 11.6^{+3.8}_{-3.1}$$

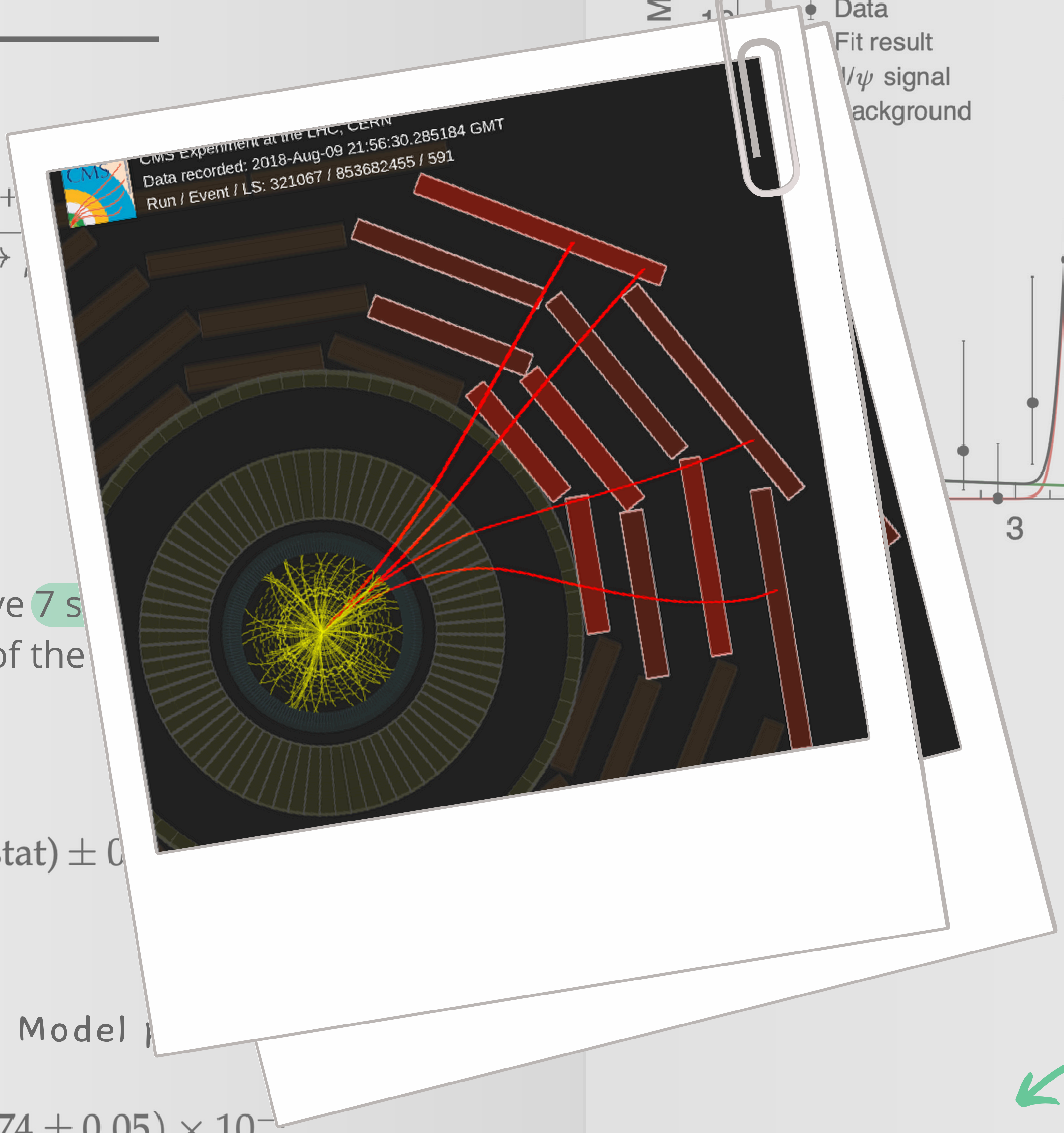
The significance of the signal is above 7 s... evaluated from the likelihood ratio of the ... the bkg-only fit

$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}\,(\text{stat}) \pm 0 \ldots$$

Standard Model p...

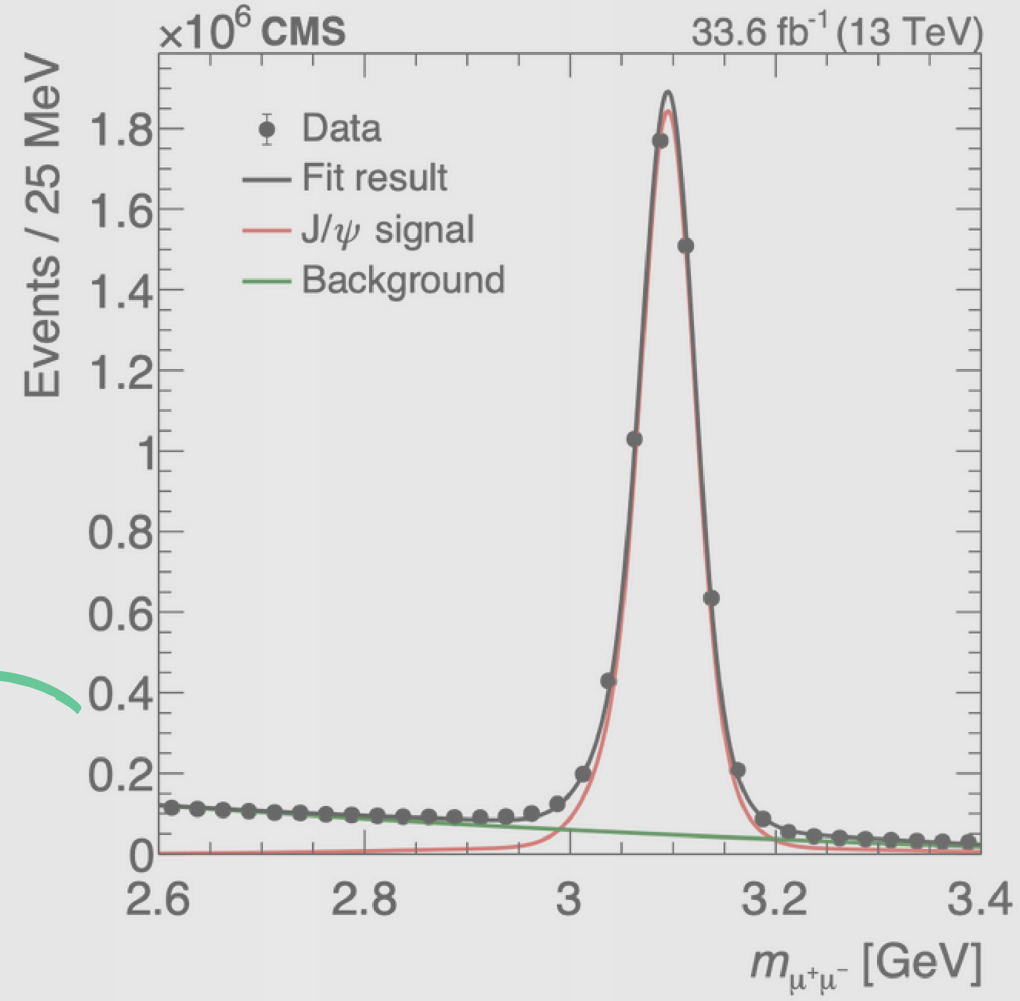
$$(9.74 \pm 0.05) \times 10^{-} \ldots$$





CLICK ME

CrystalBall + Gaussian



$$N = (5770 \pm 3) \times 10^3$$

J/ψ in 4-mu

Secondary = non prompt

Candidate selection:

- **Prompt four muons database** has been used;
- Each muon with $p_t > 500$ MeV/c and $p > 10$ GeV/c;
- For the **secondary candidates the vertex has to be displaced** with respect to the **PV** of at least 3 s.d.;
- A **BDT** is used to discriminate the signal from the background.

The efficiency, given the acceptance of the LHCb detector are:

Category	$J/\psi \to \mu^+\mu^-\mu^+\mu^-$	$J/\psi \to \mu^+\mu^-$	Ratio
Prompt	0.052%	1.992%	0.0262
Secondary	0.085%	0.518%	0.1641

much tighter selection

While the **ratio averaged from the two categories** is:

$$R_{\mathcal{B}} = (1.89 \pm 0.17 \pm 0.09) \times 10^{-5}$$

(since it is a parameter it is directly extracted from the fit result)

DATA COLLECTED BY LHCB (2016-2018)

CENTER-OF-MASS ENERGY: 13 TeV

INTEGRATED LUMINOSITY: 5.4/FB

CLICK ME

J/ψ in 4-mu

Secondary = non prompt

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- Each muon with $p_t > 500$ MeV/c and $p > 10$ GeV/c;
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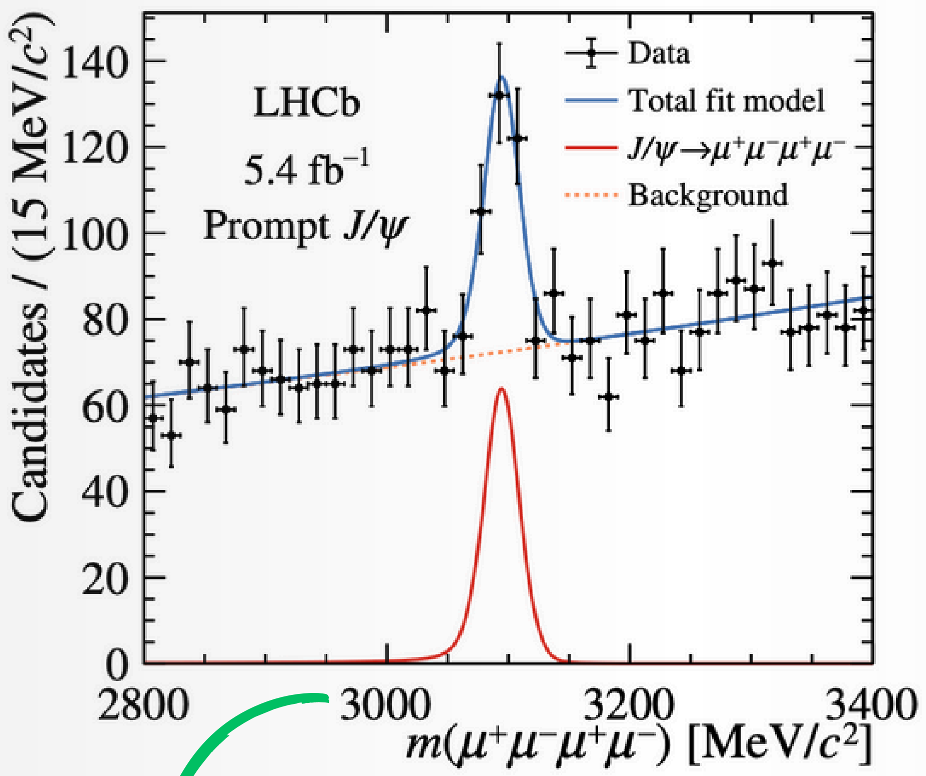
prompt candidates

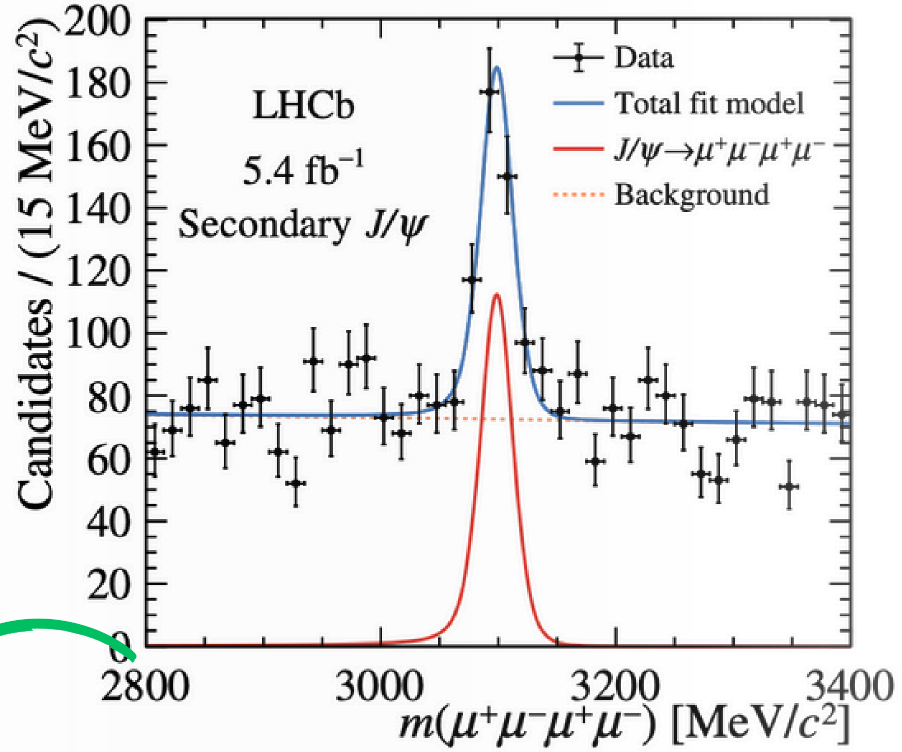


$N = 166 \pm 27$

CLICK ME

double-sided CrystalBall with same mean

secondary candidates



$N = 286 \pm 30$

J/ψ in 4-mu

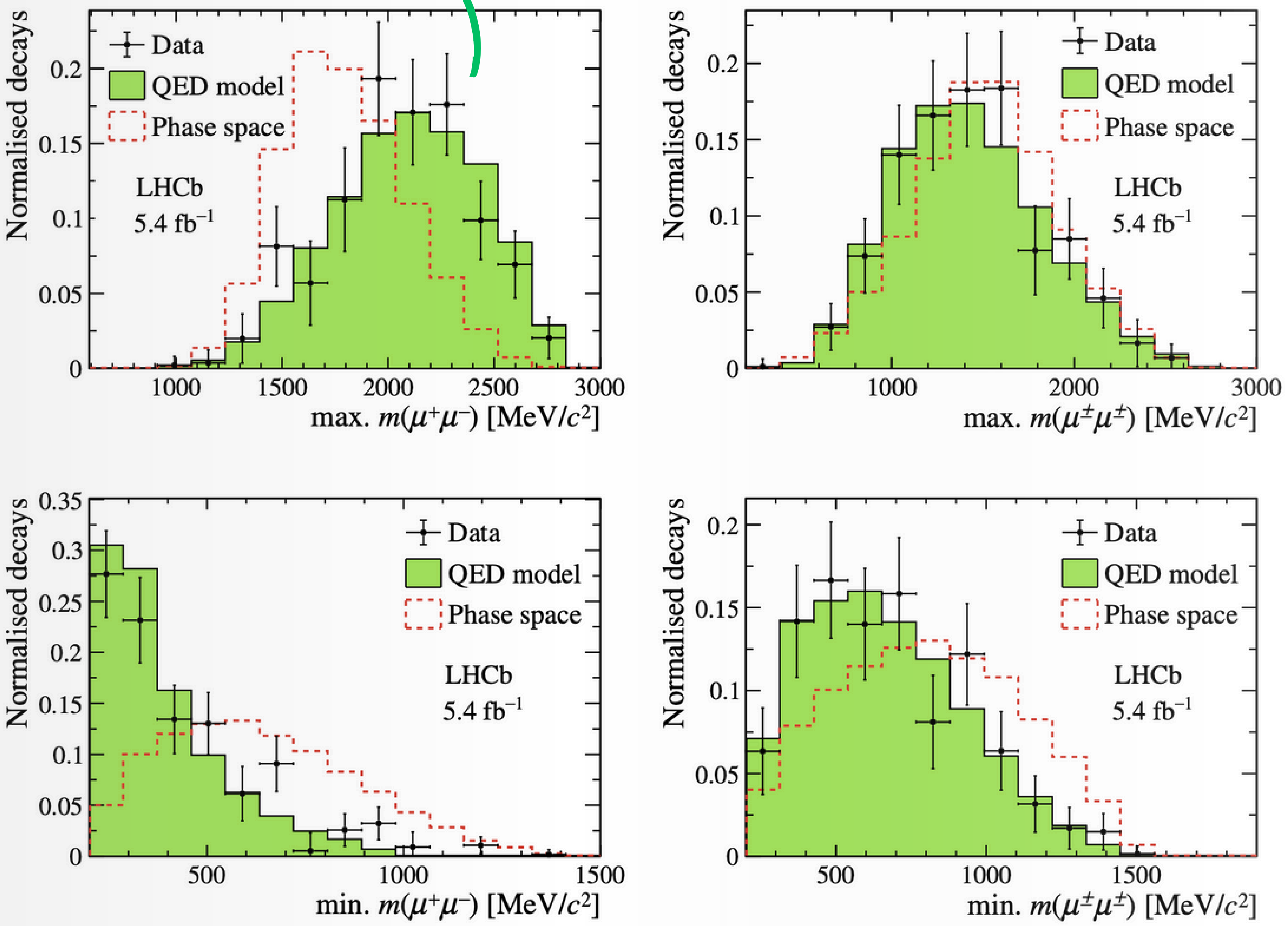
Secondary = non prompt

In general, there is an agreement between the background-subtracted data and calibrated simulation is examined in the kinematic observables of interest in the signal decays.

- The **QED model describes the data accurately at the current precision level.**
- In contrast, the model with kinematics uniformly distributed across the phase space does not match the data.

For the data, only statistical uncertainties are shown

CLICK ME



Comparison of background-subtracted data and calibrated simulation relying on the QED model in the secondary dataset

J/ψ in 4-mu

Secondary = non prompt

In general, there is an agreement between the background-subtracted data and calibrated simulation is examined in the kinematic observables of interest in the signal decays.

- The **QED model describes the data accurately at the current precision level.**
- In contrast, the model with kinematics uniformly distributed across the phase space does not match the data.

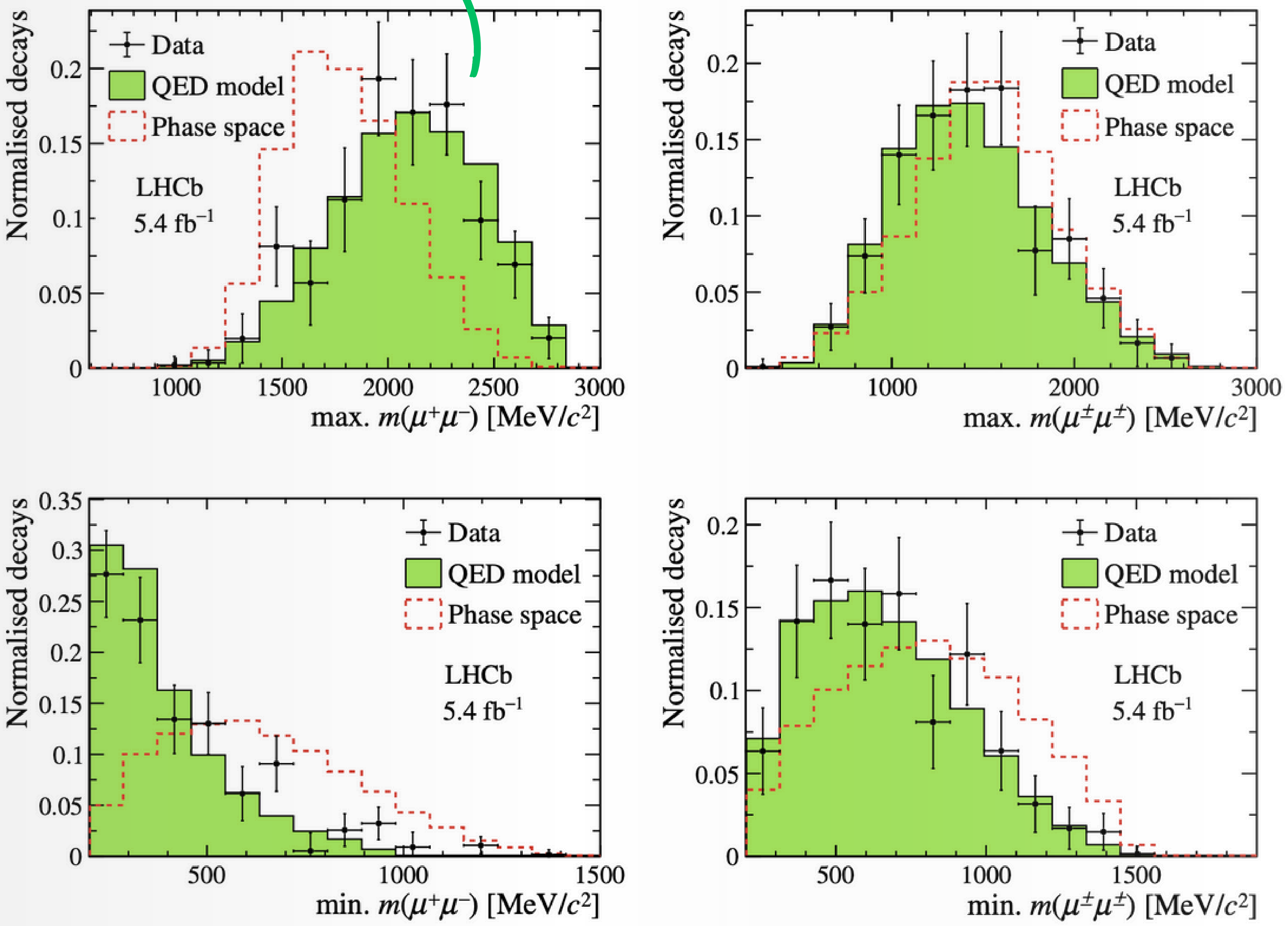
Taking into account the two categories and the known value of the di muon BR we get:

$$BR(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (1.13 \pm 0.10 \pm 0.05 \pm 0.01) \times 10^{-6}$$

DECAY IS OBSERVED WITH SIGNIFICANCE FAR ABOVE THE DISCOVERY THRESHOLD

For the data, only statistical uncertainties are shown

CLICK ME



Comparison of background-subtracted data and calibrated simulation relying on the QED model in the secondary dataset

J/Ψ AND Ψ(2S)

Eur. Phys. J. C (2024) 84:169
https://doi.org/10.1140/epjc/s10052-024-12439-9
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Regular Article - Experimental Physics

Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 4 October 2023 / Accepted: 12 January 2024

CMS
CERN-EP-2024-155
2024/06/21
CMS-BPH-22-009

Measurement of the polarizations of prompt and non-prompt J/ψ and ψ(2S) mesons produced in pp collisions at $\sqrt{s} = 13$ TeV

J/Ψ IN 4 MUONS

CMS
CERN-EP-2024-058
2024/06/10
CMS-BPH-22-006

Observation of the J/$\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

CONF-2024-001
April 2, 2024

Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

N-J/Ψ IN MPI

nature physics
Article
https://doi.org/10.1038/s41567-022-01838-y

Observation of triple J/ψ meson production in proton-proton collisi

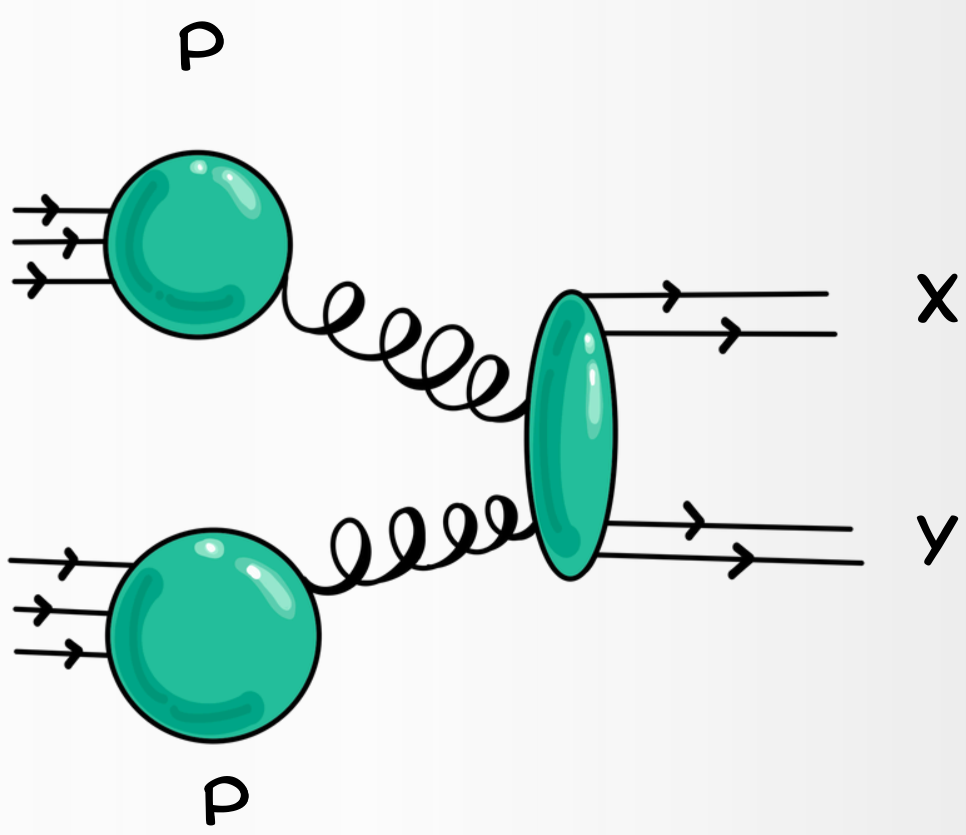
CMS Physics Analysis Summary

Contact: cms-pag-conveners-heavyions@cern.ch
2024/02/26

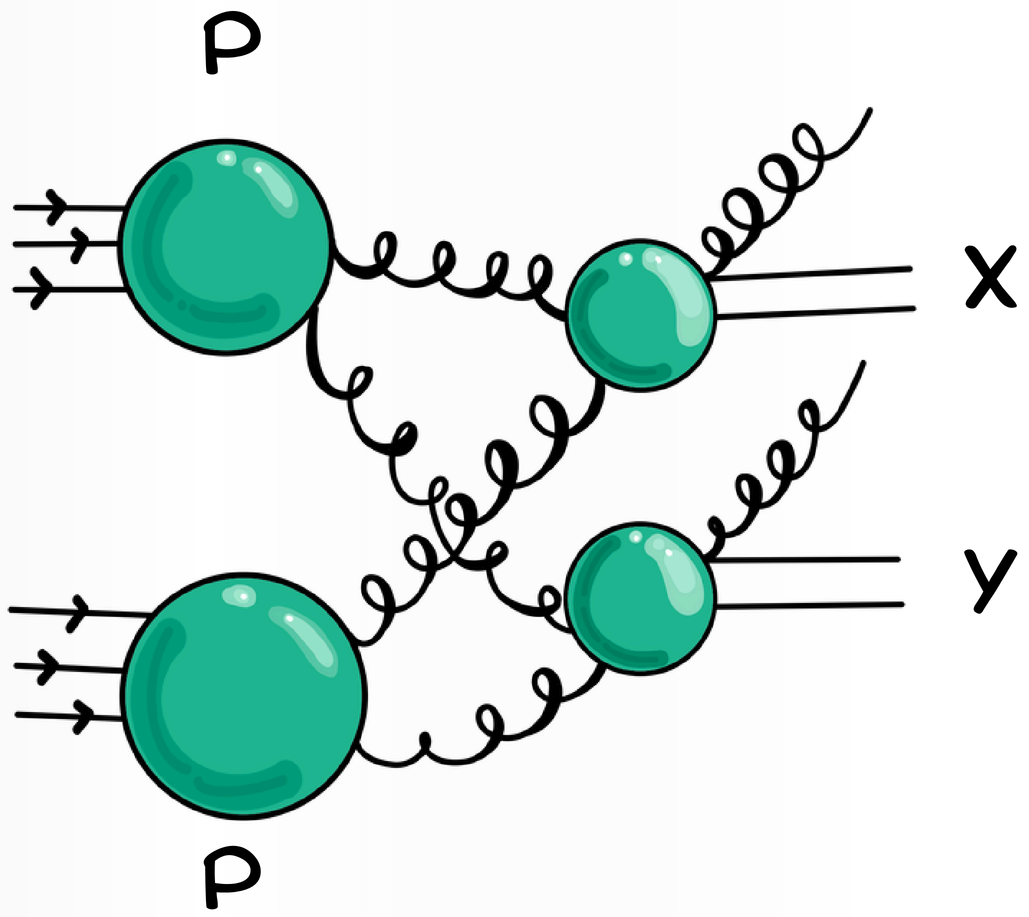
Observation of double-J/ψ meson production in pPb collisions at 8.16 TeV

Single and Double Parton Scattering

SPS



DPS



- Single-Parton Scattering (SPS) involves the production of two or more particles through a single interaction between two partons.
- The kinematics are correlated, with the neglect of additional gluon emissions.

- Double-Parton Scattering (DPS) involves the production of two particles through a double interaction between two partons from the same proton pairs.
- To simplify, the hard scattering is assumed as uncorrelated.
- Described by the pocket formula.

Triple-J/ψ in CMS

DATA COLLECTED BY CMS (2016-2018)

CENTER-OF-MASS ENERGY: 13 TeV

INTEGRATED LUMINOSITY: 131/FB

CLICK ME!

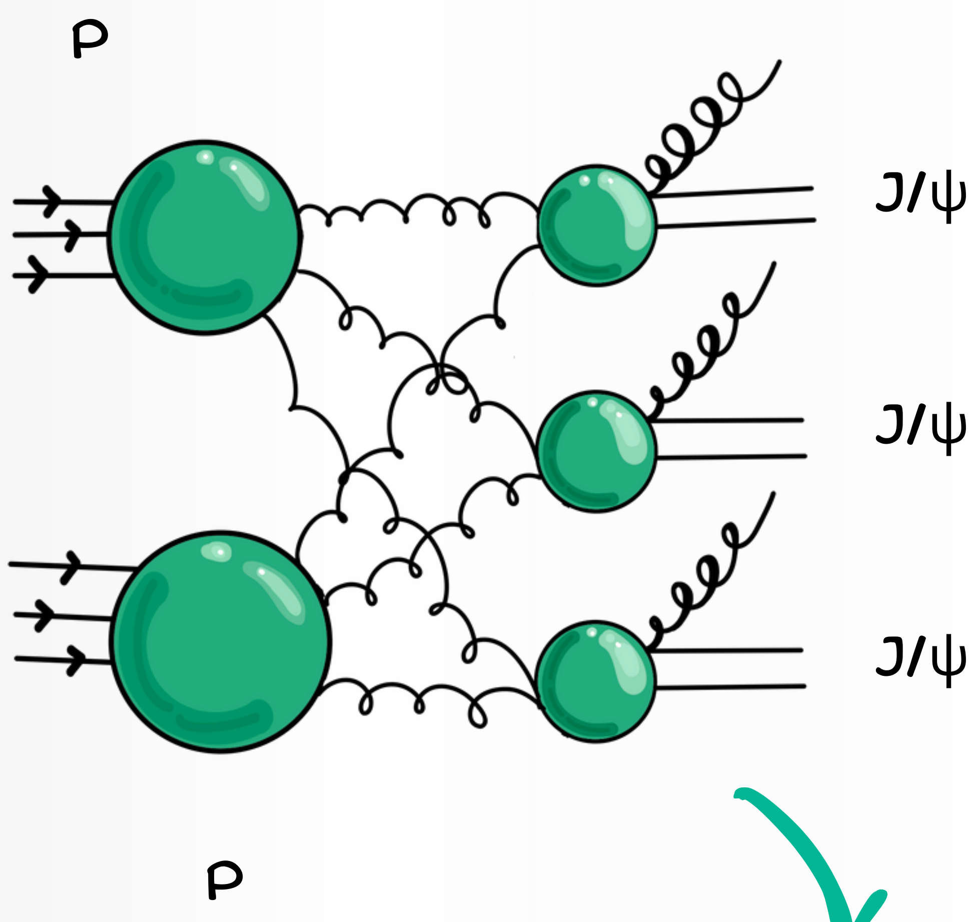
POCKET FORMULA

$$\sigma_{\text{DPS}}^{pp\to\psi_1\psi_2+X} = \left(\frac{m}{2}\right)\frac{\sigma_{\text{SPS}}^{pp\to\psi_1+X}\,\sigma_{\text{SPS}}^{pp\to\psi_2+X}}{\sigma_{\text{eff}}}$$

M = 1, 3, OR 6 (DEPENDING ON WHETHER ALL THREE, TWO, OR NONE OF THE ψ STATES ARE IDENTICAL).

$$\sigma_{\text{TPS}}^{pp\to\psi_1\psi_2\psi_3+X} = \left(\frac{m}{3!}\right)\frac{\sigma_{\text{SPS}}^{pp\to\psi_1+X}\,\sigma_{\text{SPS}}^{pp\to\psi_2+X}\,\sigma_{\text{SPS}}^{pp\to\psi_3+X}}{\sigma_{\text{eff,TPS}}^{2}}$$

N THE ABSENCE OF PARTON CORRELATIONS, THE EFFECTIVE CROSS-SECTION σ_{EFF},TPS IS CLOSELY RELATED TO ITS DPS COUNTERPART



THE SIGNAL FOR US IS FROM PROMPT CONTRIBUTION AND ALL THE POSSIBLE MIXED PROMPT+ NON-PROMPT STATES

Triple-J/ψ in CMS

- Data analysis starts by selecting **events with > 6 muons**, each passing the p_T and η criteria
- The muons are then paired to reconstruct the charmonia candidates within the kinematical and mass range acceptance.
- All selected muon pairs are further required to **share the same primary vertex (PV).**

For all muons	$p_{\mathrm{T}} > 3.5\,\mathrm{GeV}$ for $\lvert\eta\rvert < 1.2$ $p_{\mathrm{T}} > 2.5\,\mathrm{GeV}$ for $1.2 < \lvert\eta\rvert < 2.4$
For all J/ψ mesons	$p_{\mathrm{T}} > 6\,\mathrm{GeV}$ and $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3\,\mathrm{GeV}$

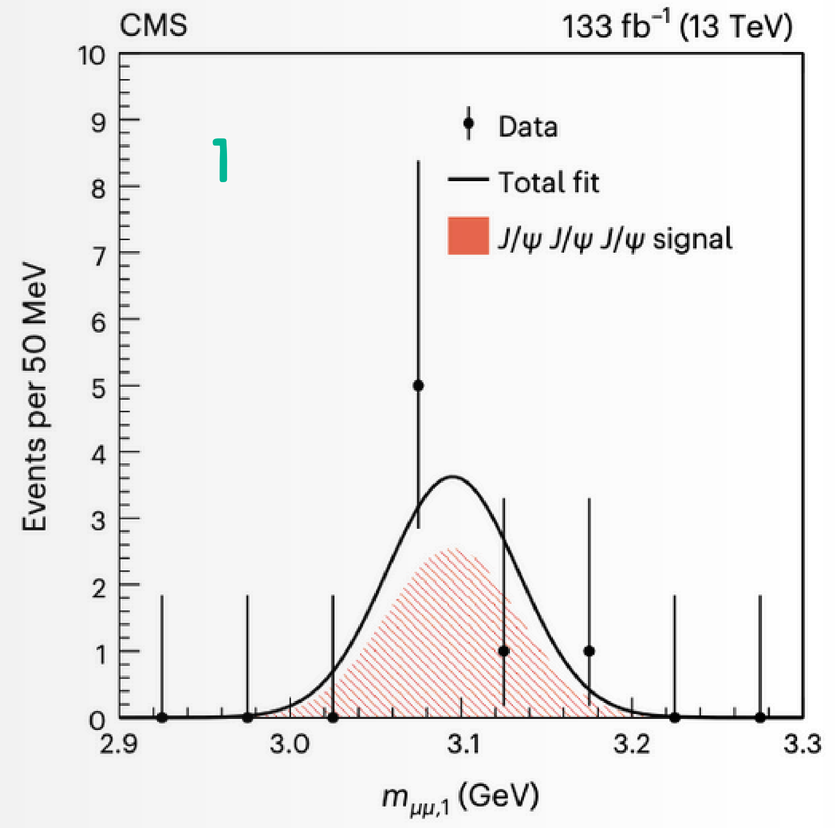
The total events found are:

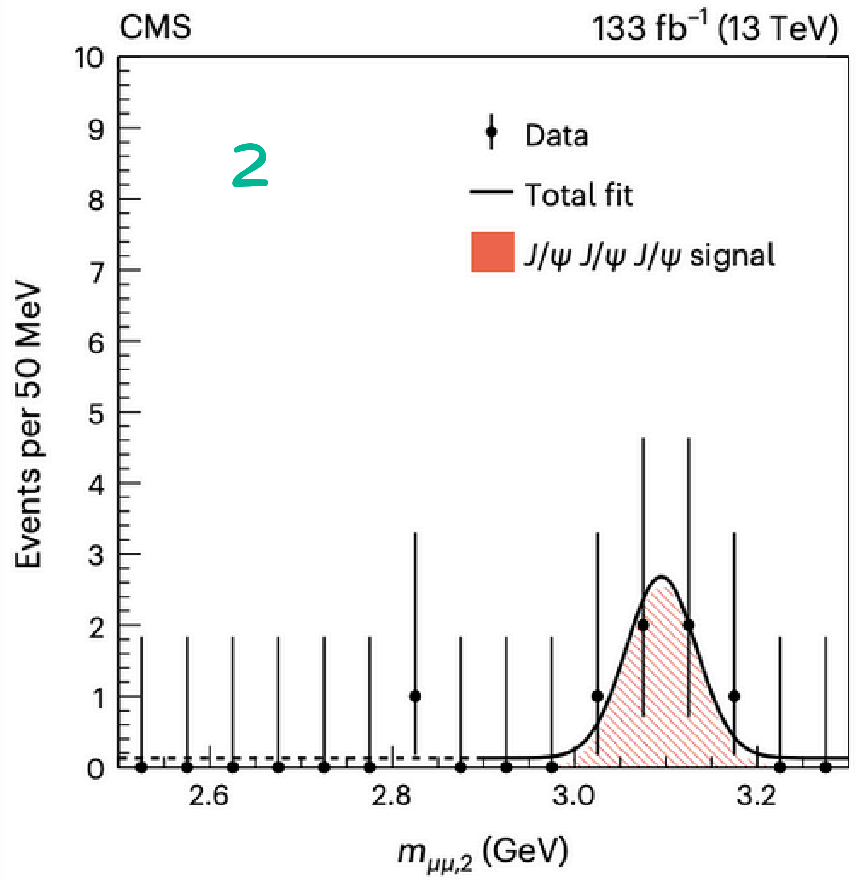
$$N^{3J/\psi}_{\text{sign}} = 5.0^{+2.6}_{-1.9} + N_{bkg} = 1^{+1.4}_{-0.8}$$

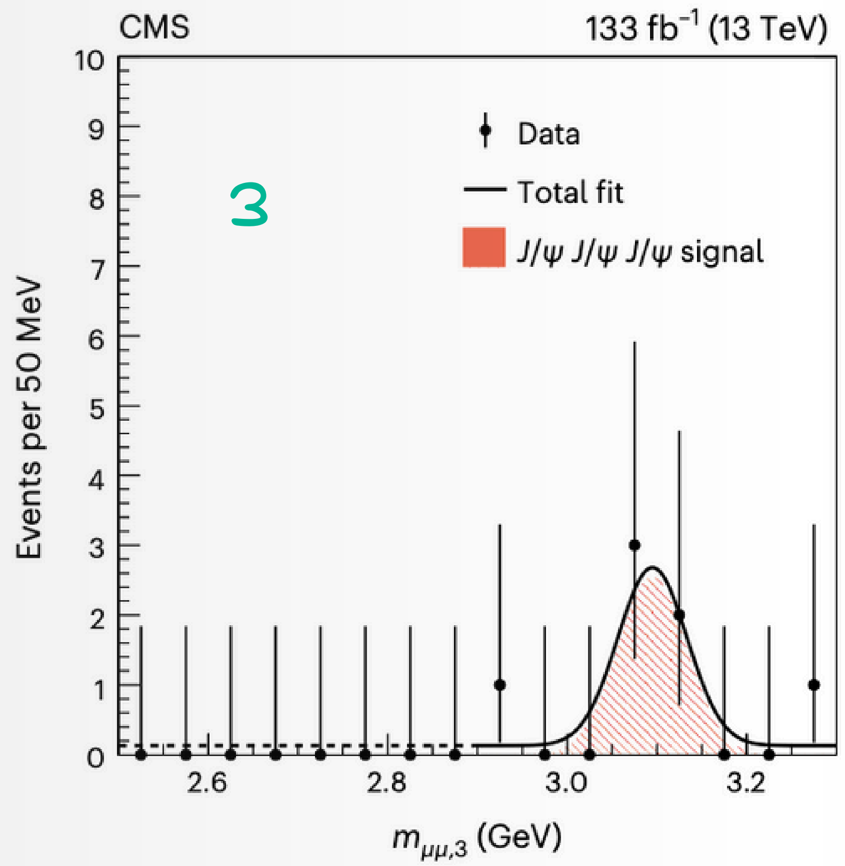
6.7 STD. DEV. FROM THE NULL HYPOTESIS

$$\sigma(pp \to J/\psi J/\psi J/\psi X) = 272 + 141(\text{stat}) \pm 17(\text{syst})\text{fb}$$

CLICK ME!







6 % SPS
74% DPS
20% TPS

Triple-J/ψ in CMS

CLICK ME!

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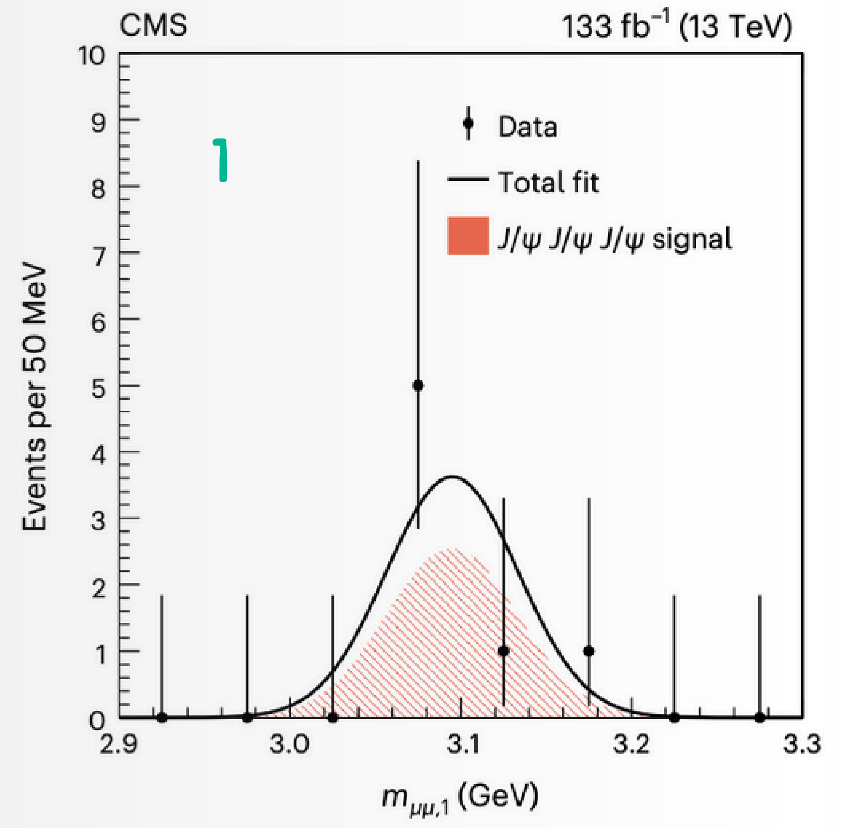
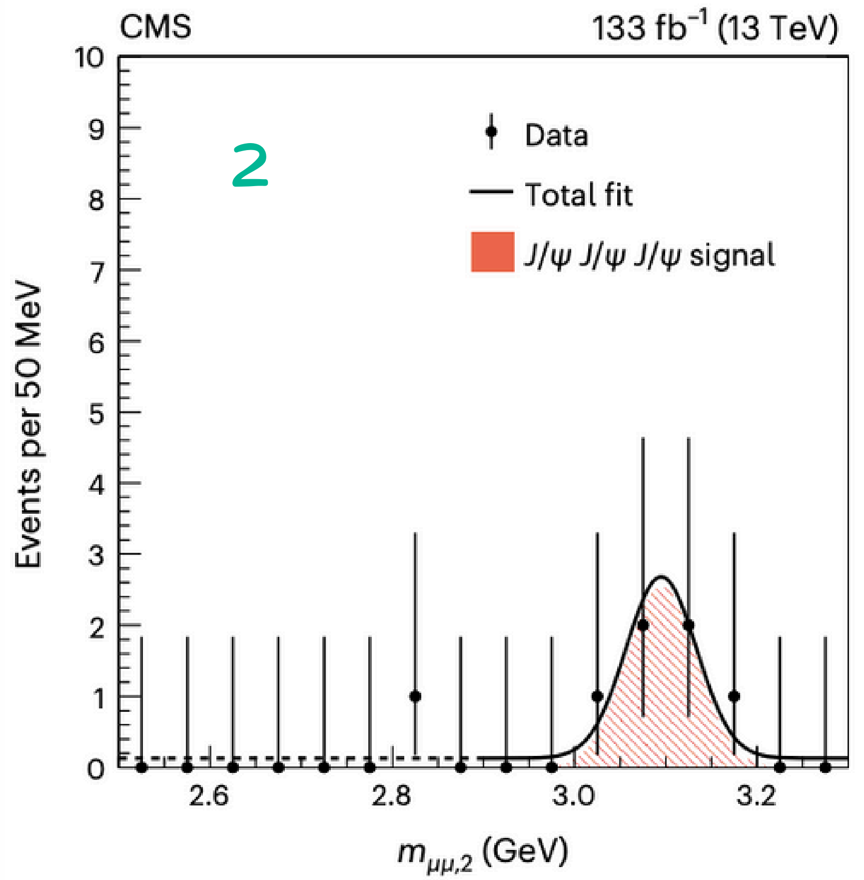
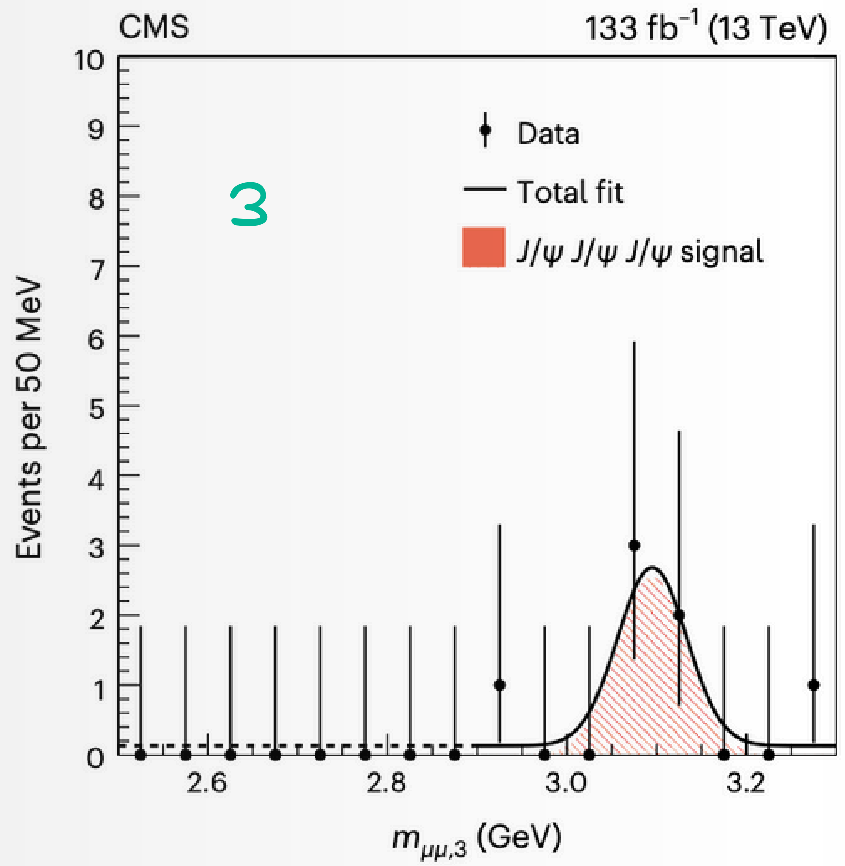
$$\sigma_{\text{eff, DPS}} = 2.7^{+1.4}_{-1.0}(\text{exp}) \pm^{1.5}_{-1.0}\,(\text{theo})\ \text{mb}$$

$$\sigma_{\text{eff,TPS}} = 0.82\sigma_{\text{eff,DPS}} = 2.2\ \text{mb}$$







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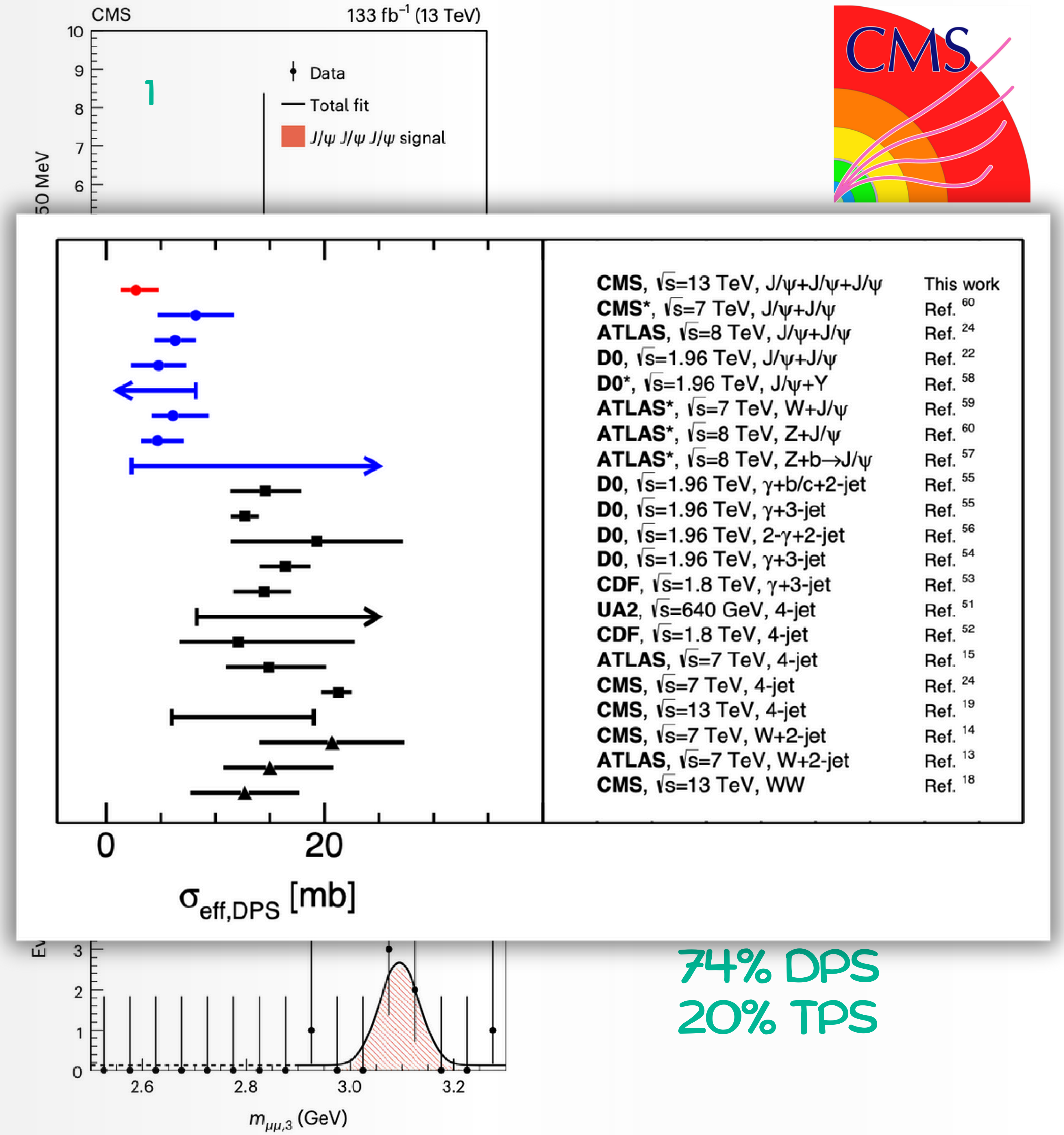
CLICK ME!



74% DPS
20% TPS

Di-J/ψ in CMS

82
Pb
lead
207.2

DATA COLLECTED BY CMS (2016)

CENTER-OF-MASS ENERGY: 8.16 TeV

INTEGRATED LUMINOSITY: 174.6/NB

CLICK ME

Main goals of the analysis:

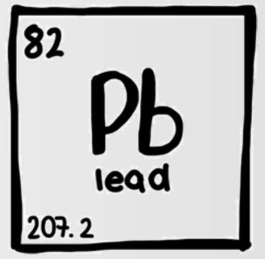
- Measure the production cross-section of the di-J/ψ in the di-muon (or di-electron) channel.
- Estimate the SPS/DPS contribution.

TO STUDY THE B-DEPENDENCE IN THE N-PDFS

TO CLARIFY THE SPS PRODUCTION OF MULTIPLE QUARKONIUM STATES

TO IMPROVE OUR UNDERSTANDING OF DPS PROCESSES

Di-J/ψ in CMS



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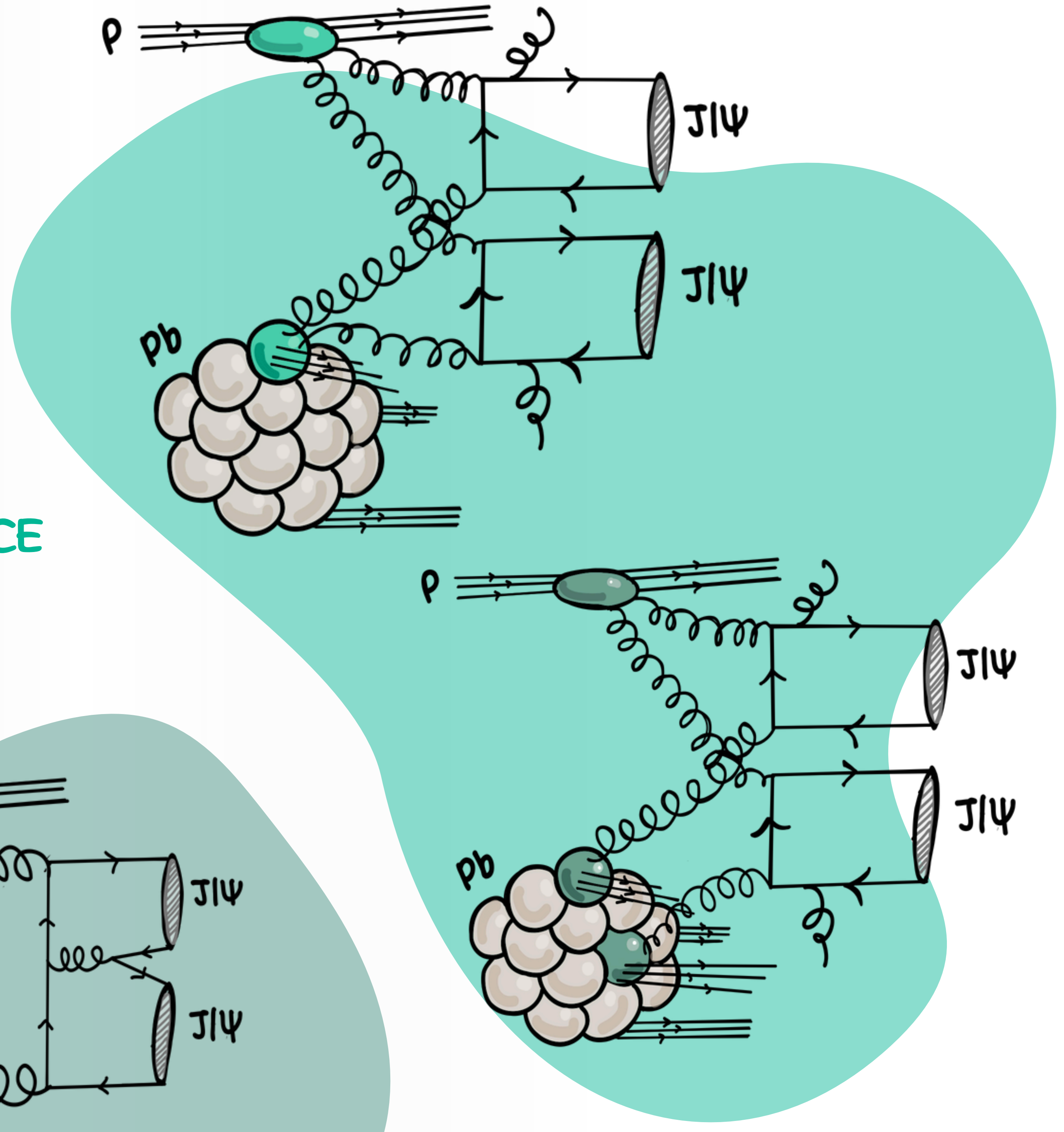
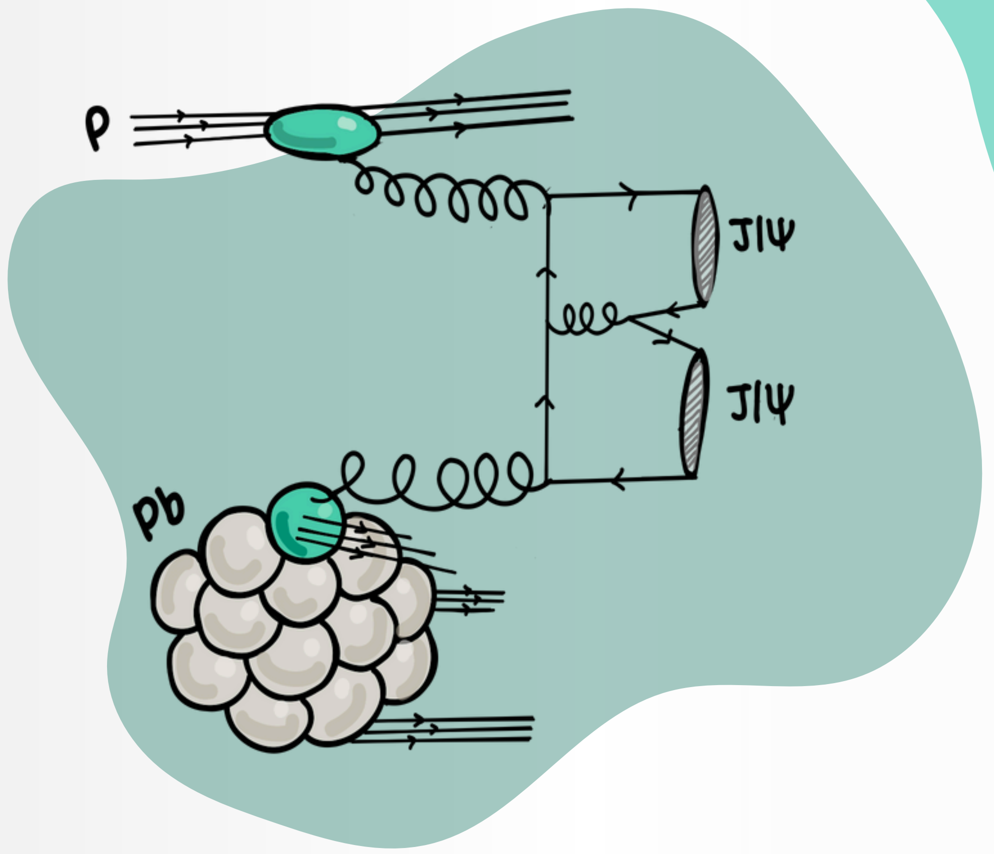




The pocket formula

POCKET FORMULA

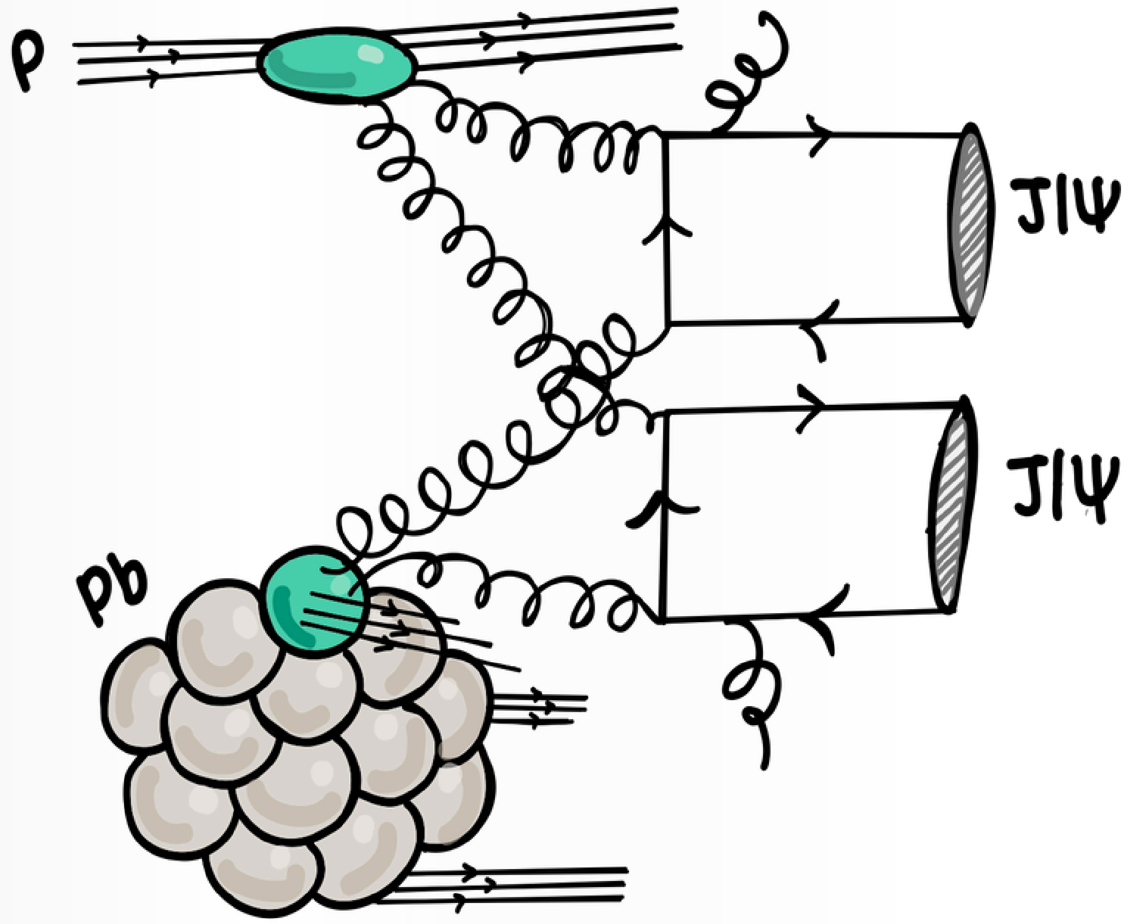
$$\sigma^{pp\to\psi_1\psi_2+X}_{\text{DPS}} = \left(\frac{m}{2}\right)\frac{\sigma^{pp\to\psi_1+X}_{\text{SPS}}\,\sigma^{pp\to\psi_2+X}_{\text{SPS}}}{\sigma_{\text{eff}}}$$

P-A POCKET FORMULA

$$\sigma^{p\text{Pb}\to J/\psi J/\psi+X}_{\text{DPS}} = \left(\frac{1}{2}\right)\frac{\sigma^{p\text{Pb}\to J/\psi+X}_{\text{SPS}}\,\sigma^{p\text{Pb}\to J/\psi+X}_{\text{SPS}}}{\sigma_{\text{eff,pA}}}$$

WITH

$$\sigma_{\text{eff,pA}} = \frac{A\sigma_{\text{eff}}}{1+\sigma_{\text{eff}}F_{pA}/A'}$$



$$F_{pA} = \frac{(A-1)}{A}\int d^2b\,T^2(b)$$

INTEGRAL OVER IMPACT PARAMETER OF THE SQUARED PA TRANSVERSE PROFILE, WHICH CAN BE DETERMINED THROUGH A GLAUBER MONTE CARLO MODEL

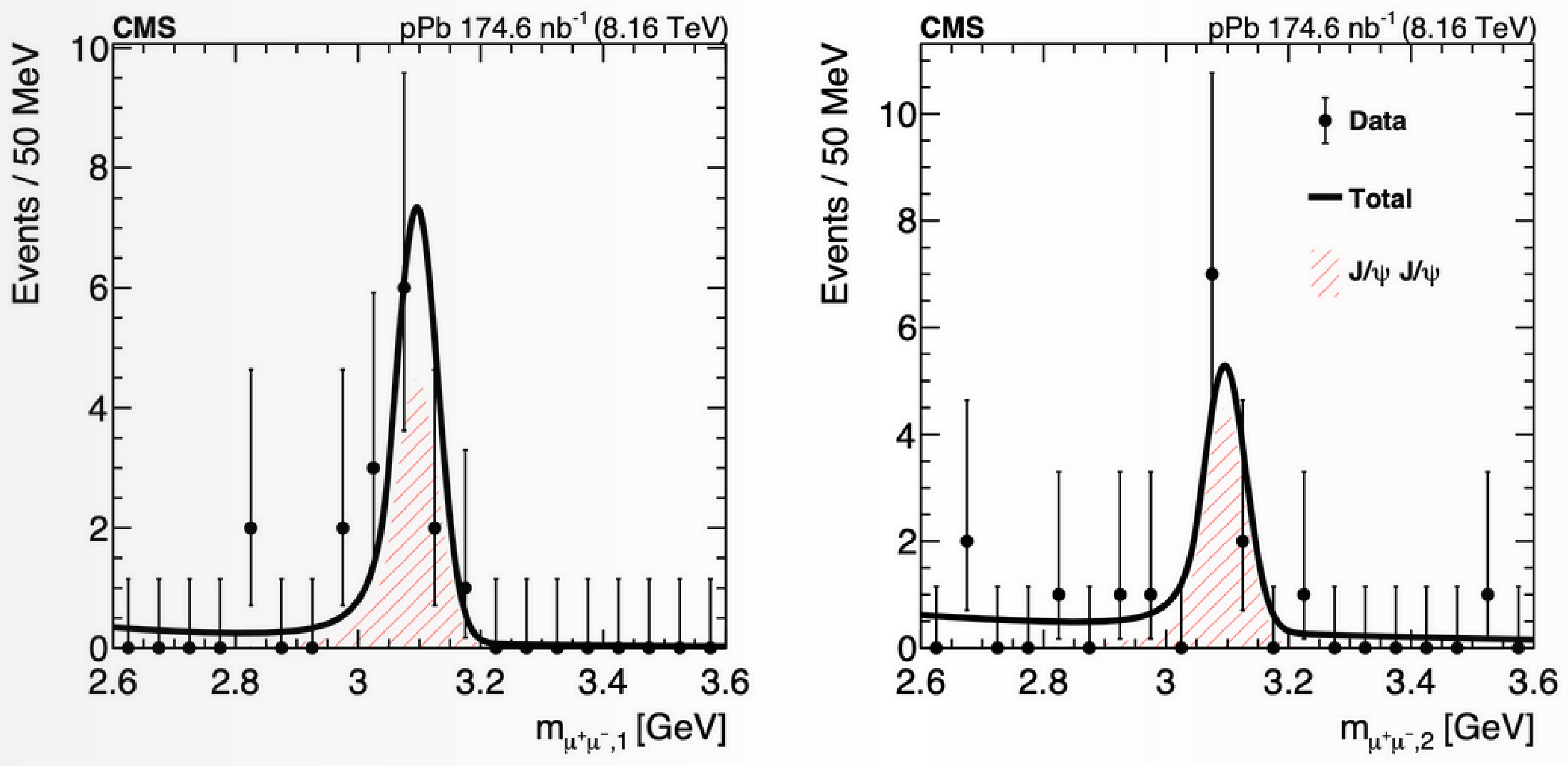
Di-J/ψ in CMS

CLICK ME

The J/ψs are reconstructed in the di-muon channel. The additional request for the four muons to originate from the same vertex suppresses the non-prompt contribution.

The measured signal yield is:

$$N_{\text{sign}} \equiv N(J/\psi_1^{\text{sign}}, J/\psi_2^{\text{sign}}) = 8.5 \pm 3.4 \text{ events}$$



$$\sigma = 4.9$$

STANDARD DEVIATIONS WHEN IMPOSING N SIGNAL EVENTS = 0

$$\sigma(pPb \to J/\psi J/\psi + X) = 22.0 \pm 8.9(\text{stat}) \pm 1.5(\text{syst}) \text{ nb}$$

Di-J/ψ in CMS

82 Pb lead 207.2

CLICK ME

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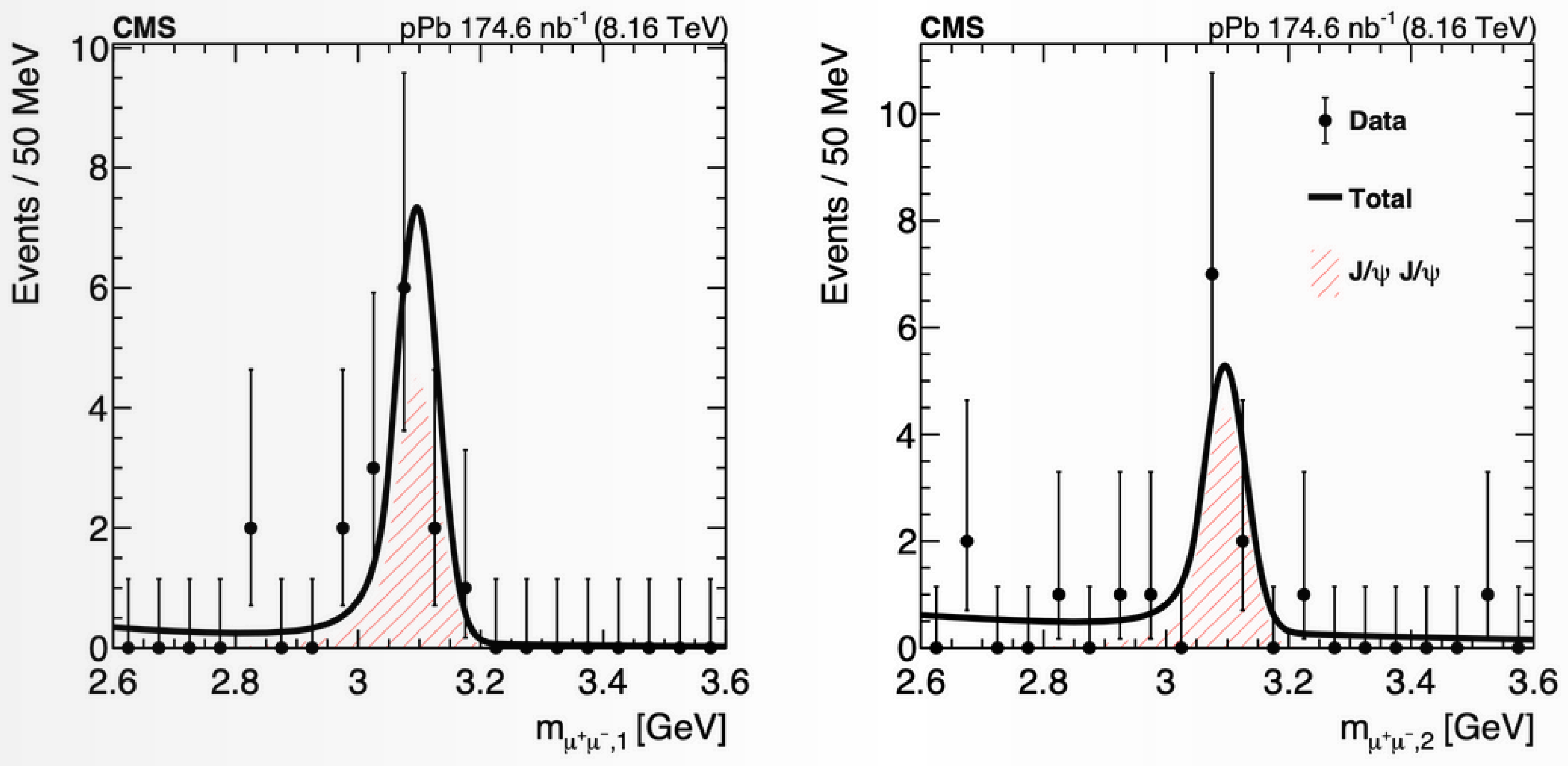

To confirm the observation were also analyzed the events where the J/ψ are reconstructed one in the di-muon channel, and the other in the di-electron channel.

The measured signal yield is:

$$N_{\text{sign}} \equiv N(J/\psi_1^{\text{sign}}, J/\psi_2^{\text{sign}}) = 5.7 \pm 4.0 \text{ events}$$

$\sigma = 2.3$ STANDARD DEVIATIONS WHEN IMPOSING N SIGNAL EVENTS = 0

Di-J/ψ in CMS

82 Pb lead 207.2

CLICK ME

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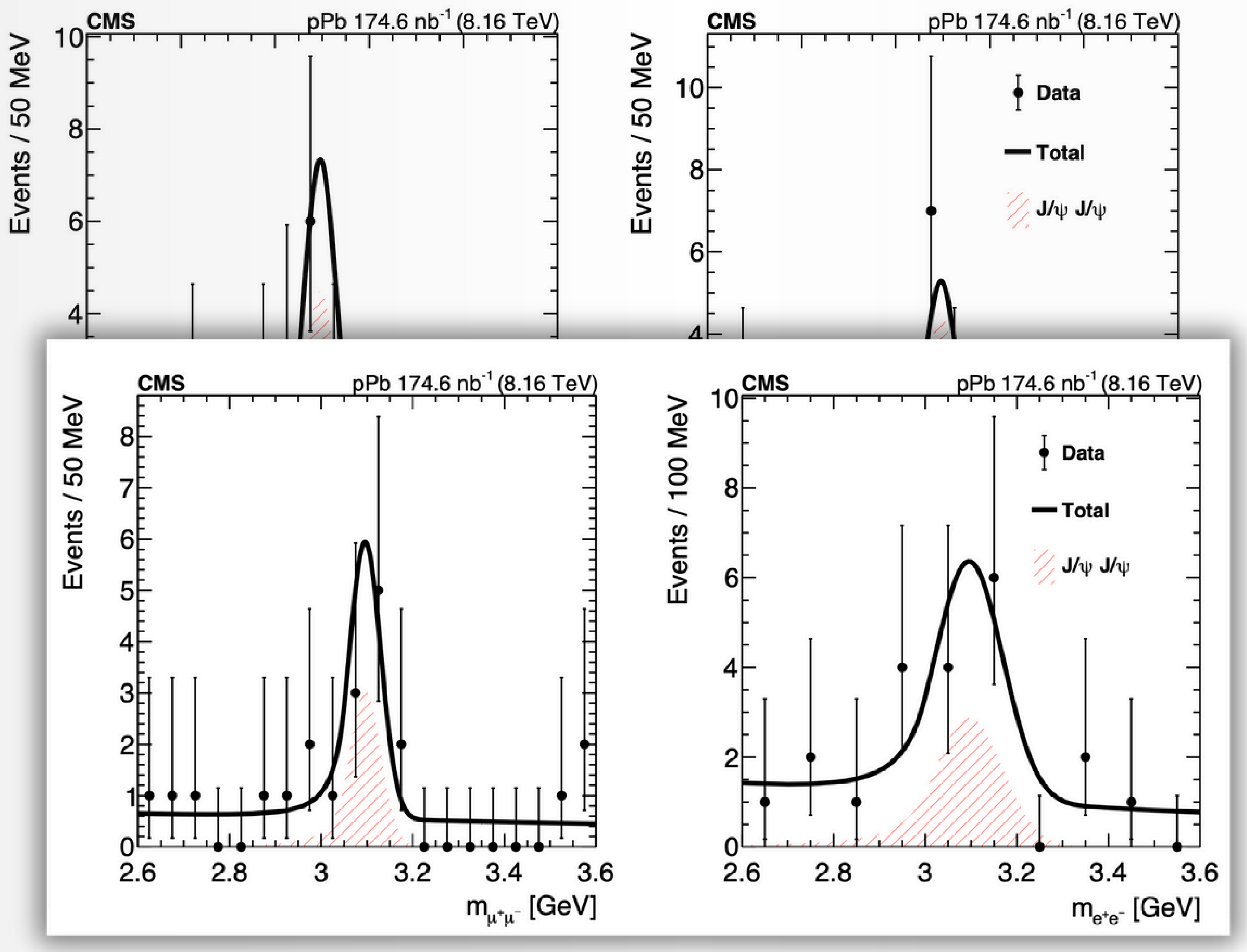

Di-J/ψ in CMS

CLICK ME

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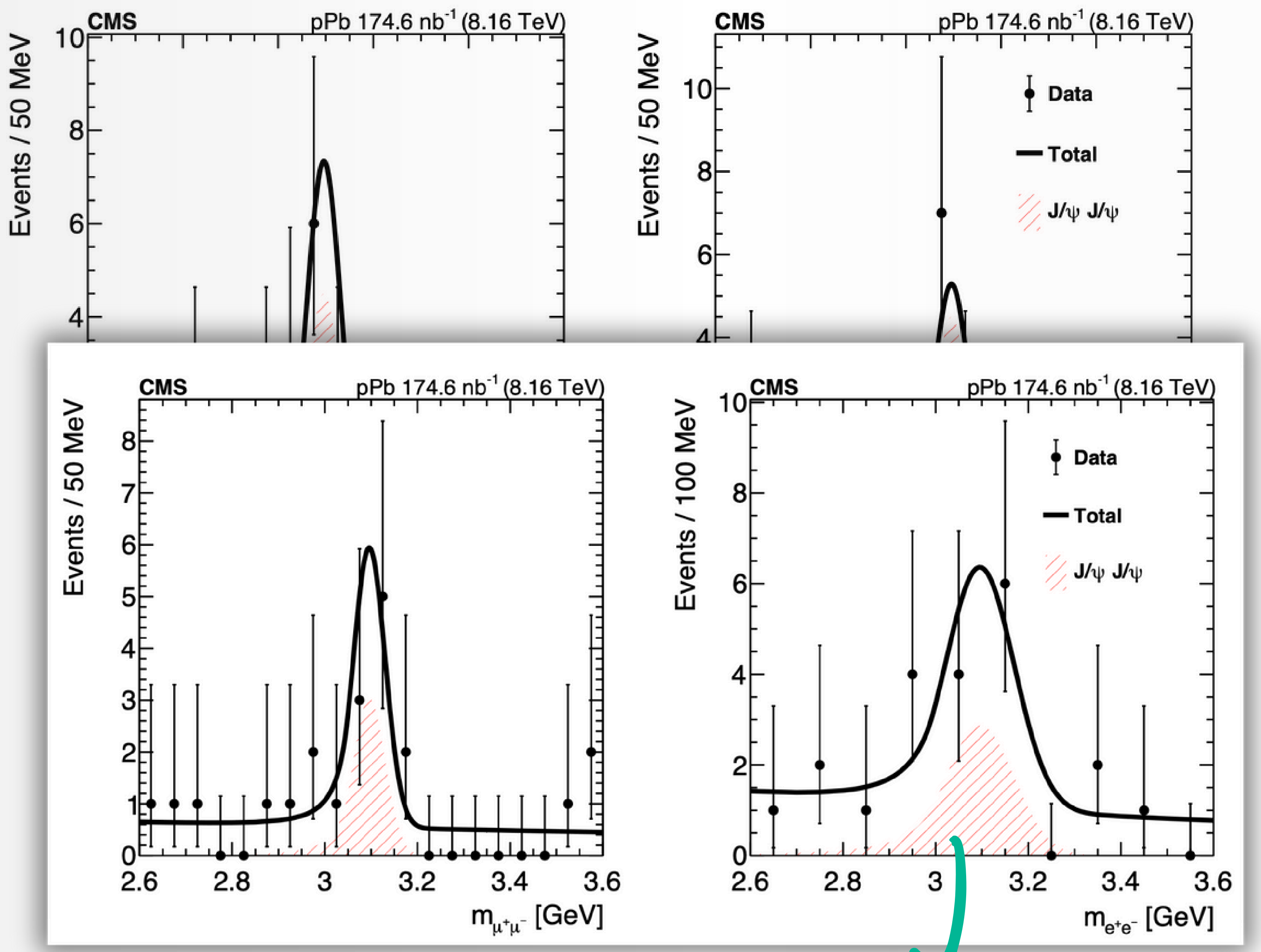


THIS LATTER CHANNEL HAS A LARGER BACKGROUND BUT INCREASES THE TOTAL SIZE OF THE DATA SAMPLE PROVIDING A CROSS-CHECK

CLICK ME

Di-J/ψ in CMS

82 Pb lead 207.2

Due to the limited size of our signal data sample, we cannot apply a 2D template-fit of the measured Δϕ–Δy distributions, with shapes dictated by the theoretical expectations, to extract the absolute normalization of the poorly known SPS di-J/ψ yields

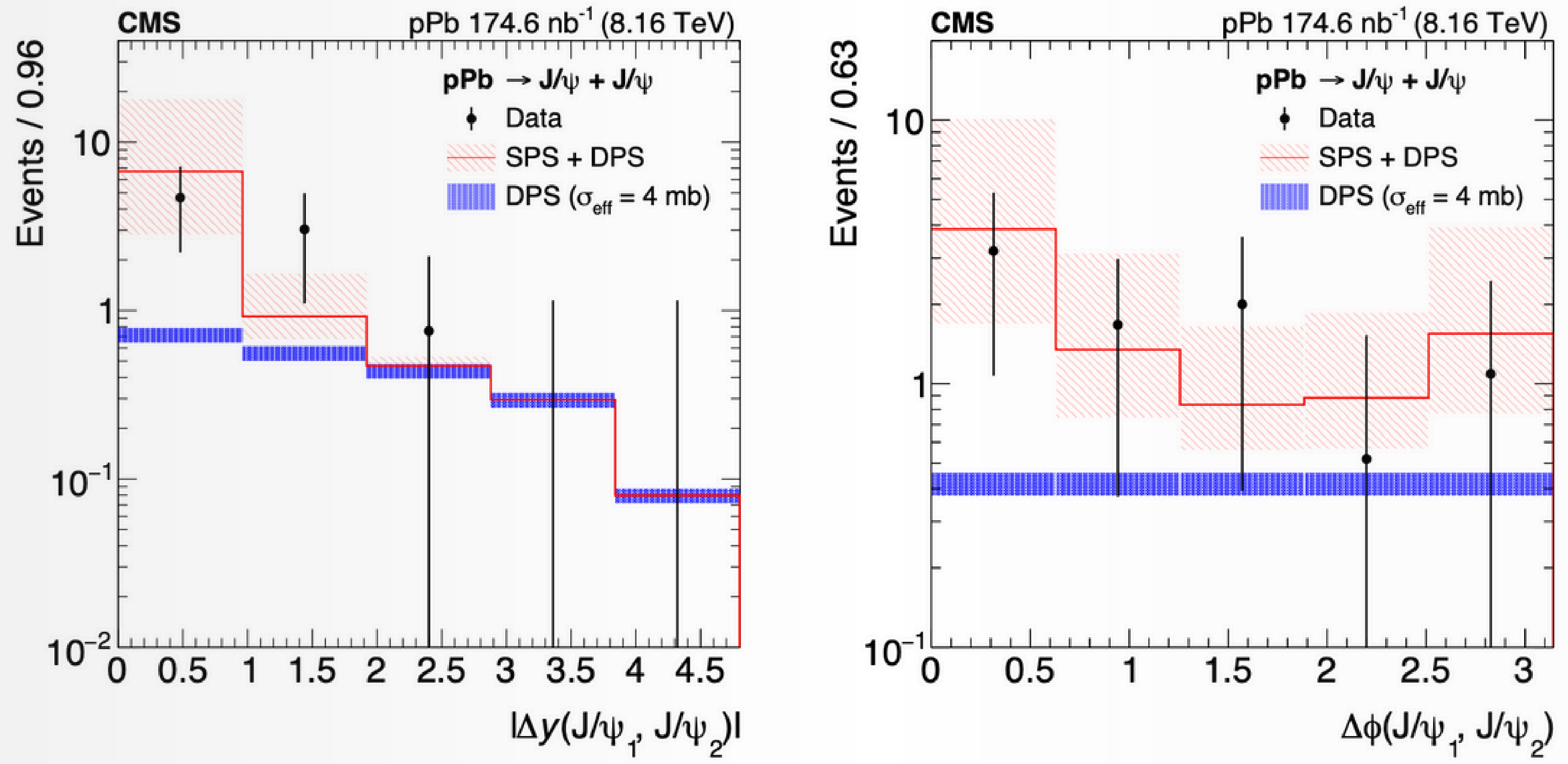
INSTEAD

- We identify a phase-space region where the SPS contribution is expected to be minimal and then constrain the expected size of the DPS yield.
- We perform a 1D fit on the Δy variable. Using a data-driven DPS template we fit the weighted data in the DPS-dominated region of Δy > 1.92

$$N_{\text{DPS}} = 2.1 \pm 2.4 \quad \text{et} \quad N_{\text{SPS}} = 6.4 \pm 4.2$$

$$\sigma_{\text{DPS}}^{pPb\to J/\psi J/\psi+X} = 5.4 \pm 6.2\,(\text{stat}) \pm 0.4\,(\text{syst})\,\text{nb}$$

$$\sigma_{\text{SPS}}^{pPb\to J/\psi J/\psi+X} = 16.5 \pm 10.8\,(\text{stat}) \pm 0.1\,(\text{syst})\,\text{nb}$$

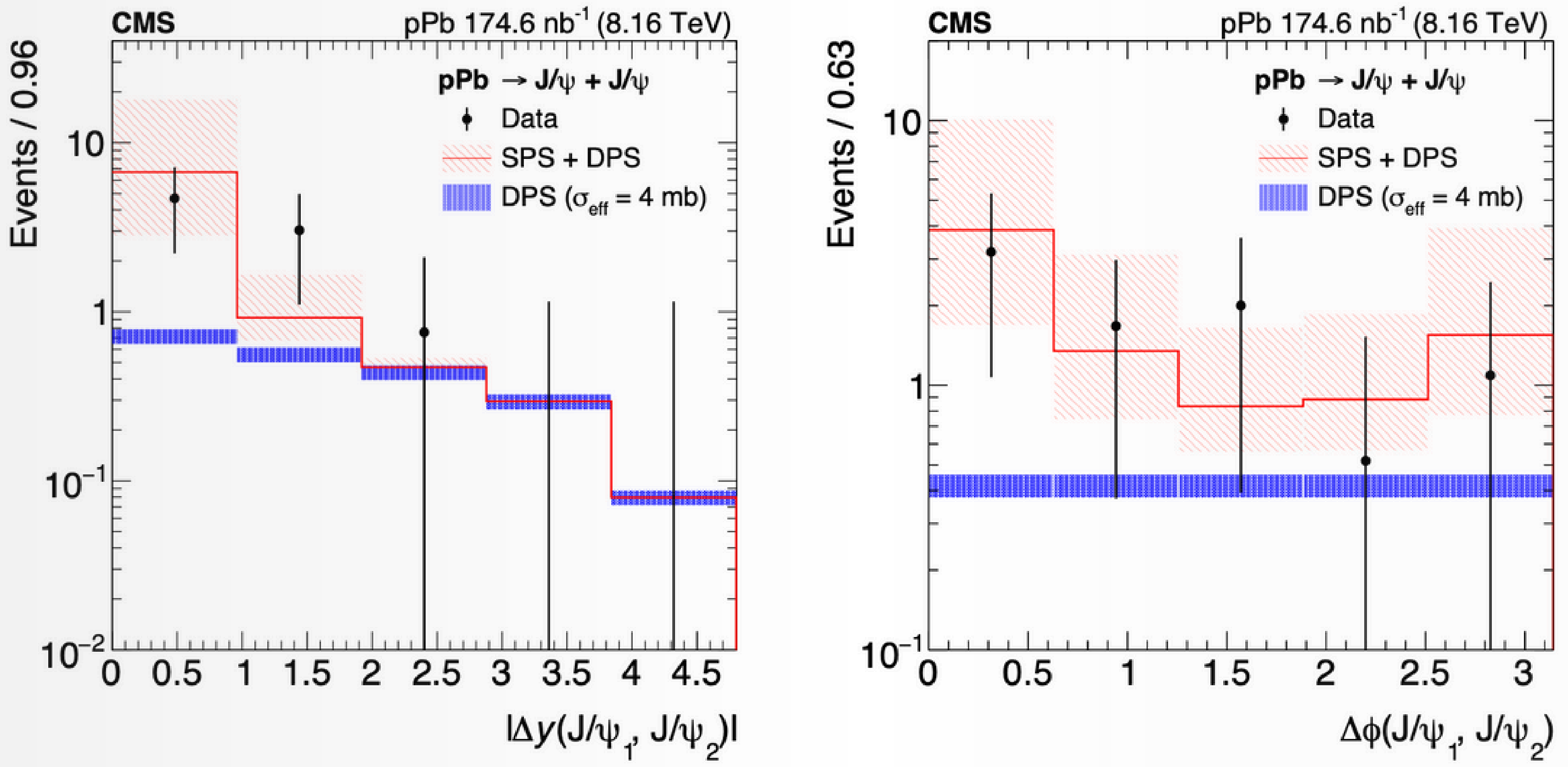


THE ΔY › 2 REGION IS FREE FROM SPS CONTRIBUTIONS AND THEREFORE ANY SIGNAL COUNT MEASURED THERE IS DOMINATED BY DPS PRODUCTION

Di-J/ψ in CMS

82 Pb lead 207.2

Due to the limited size of our signal data sample, we cannot apply a 2D template-fit of the measured Δϕ–Δy distributions, with shapes dictated by the theoretical expectations, to extract the absolute normalization of the poorly known SPS di-J/ψ yields



INSTEAD

- We identify a phase-space region where the SPS contribution is expected to be minimal and then constrain the expected size of the DPS yield.
- We perform a 1D fit on the Δy variable. Using a data-driven DPS template we fit the weighted data in the DPS-dominated region of Δy > 1.92

$$N_{\rm DPS} = 2.1 \pm 2.4 \quad \text{et} \quad N_{\rm SPS} = 6.4 \pm 4.2$$

$$\sigma_{\rm eff,pA} = \left(\frac{1}{2}\right)\frac{\sigma_{\rm SPS}^{p{\rm Pb}\to J/\psi+X}\,\sigma_{\rm SPS}^{p{\rm Pb}\to J/\psi+X}}{\sigma_{\rm DPS}^{p{\rm Pb}\to J/\psi J/\psi+X}} = 0.53^{+\infty}_{-0.2}\ {\rm b}$$

THE ARBITRARILY LARGE UPPER UNCERTAINTY THAT INDICATES THAT THE SPS YIELD ALONE WOULD BE COMPATIBLE WITH THE DATA, AND THEREFORE THAT DPS CONTRIBUTIONS COULD BE IN PRINCIPLE ABSENT

$$\sigma_{\rm DPS}^{p{\rm Pb}\to J/\psi J/\psi+X} = 5.4 \pm 6.2\,({\rm stat}) \pm 0.4\,({\rm syst})\ {\rm nb}$$

$$\sigma_{\rm SPS}^{p{\rm Pb}\to J/\psi J/\psi+X} = 16.5 \pm 10.8\,({\rm stat}) \pm 0.1\,({\rm syst})\ {\rm nb}$$

Di-J/ψ in CMS

82 Pb lead 207.2

CLICK ME

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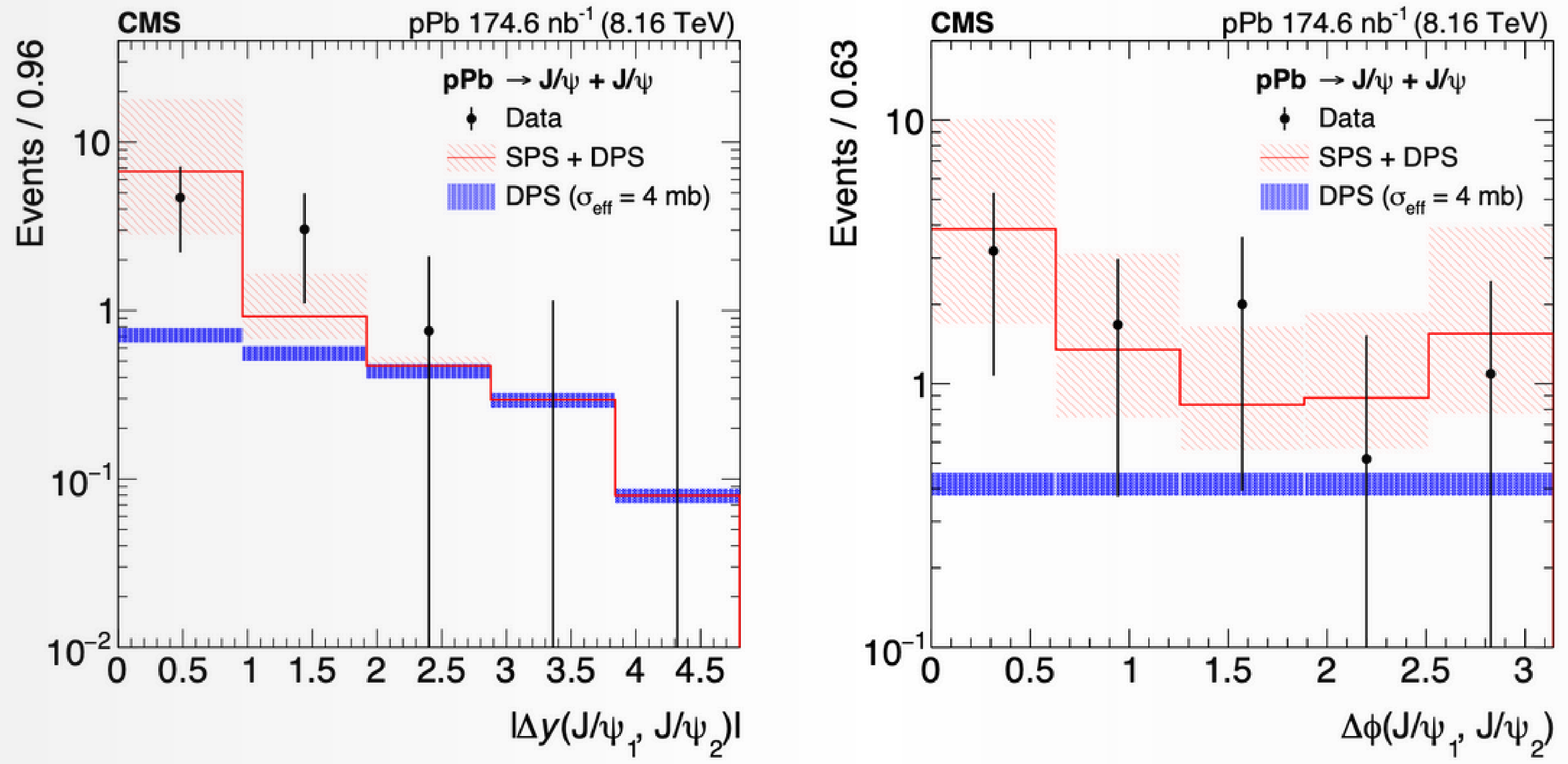

$$\sigma_{\text{eff,pA}} = \left(\frac{1}{2}\right)\frac{\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi+X}\,\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi+X}}{\sigma_{\text{DPS}}^{p\text{Pb}\to J/\psi J/\psi+X}} = 0.53^{+\infty}_{-0.2}\ \text{b}$$

$$\sigma_{\text{eff}} = \frac{\sigma_{\text{eff,pA}}}{A - \sigma_{\text{eff,pA}} F_{\text{pA}}/A} = 4.0^{+\infty}_{-1.5}\ \text{mb}$$

$$A = 208 \qquad F_{\text{pA}} = 29.5\,\text{mb}^{-1}$$

CLICK ME

Di-J/ψ in CMS

82 Pb lead 207.2

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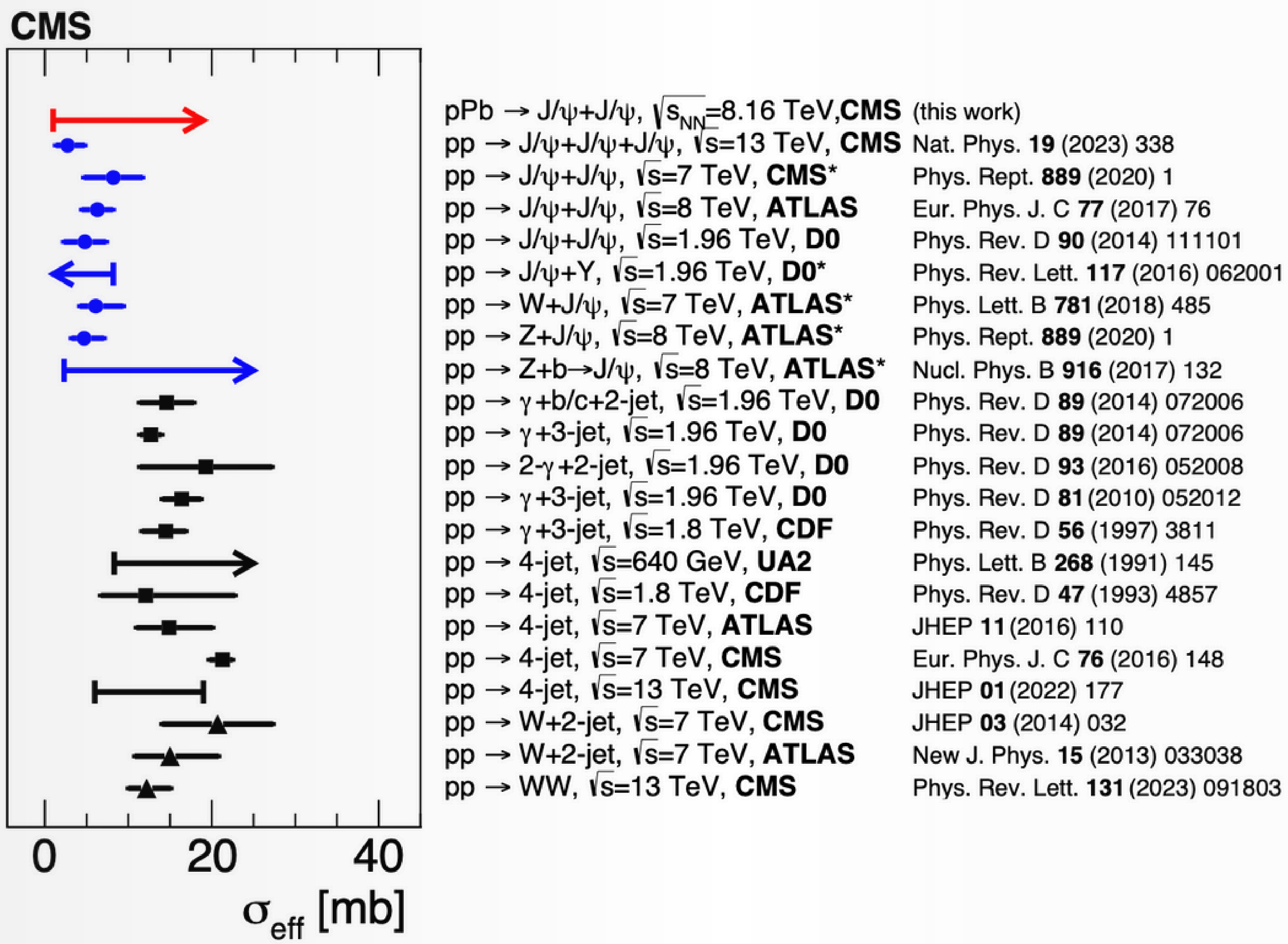

J/Ψ AND Ψ(2S)

Eur. Phys. J. C (2024) 84:169
https://doi.org/10.1140/epjc/s10052-024-12439-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 4 October 2023 / Accepted: 12 January 2024
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CMS

CERN-EP-2024-155
2024/06/21

CMS-BPH-22-009

Measurement of the polarizations of prompt and non-prompt J/ψ and $\psi(2S)$ mesons produced in pp collisions at $\sqrt{s} = 13$ TeV

J/Ψ IN 4 MUONS

CMS

CERN-EP-2024-058
2024/06/10

CMS-BPH-22-006

Observation of the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

LHCb-CONF-2024-001
April 2, 2024

Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

J/Ψ & Υ(NS) IN PB-PB

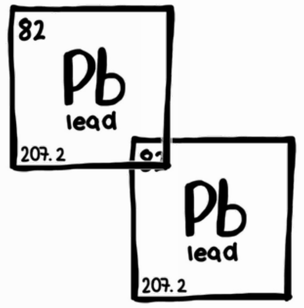
PHYSICAL REVIEW LETTERS 133, 022302 (2024)

Observation of the $\Upsilon(3S)$ Meson and Suppression of Υ States in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. Tumasyan et al.*
(CMS Collaboration)

(Received 29 March 2023; revised 14 January 2024; accepted 28 May 2024; publishe...

The production of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons in lead-lead (Pb-Pb) and proton-proton (p...
studied in their dimuon decay channel using the CMS detector at the LHC. The $\Upsilon(3S)$ me...



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN-EP-2023-054
22 March 2023

Measurements of inclusive J/ψ production at midrapidity and forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration

J/Ψ IN MPI

nature physics

Article

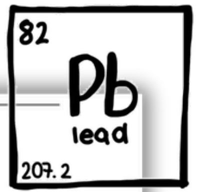
https://doi.org/10.1038/s41567-022-01838-y

Observation of triple J/ψ meson production in proton-proton collisi...

CMS Physics Analysis Summary

Contact: cms-pag-conveners-heavyions@cern.ch
2024/02/26

Observation of double-J/ψ meson production in pPb collisions at 8.16 TeV



Inclusive J/ψ

The goal of the analysis were:

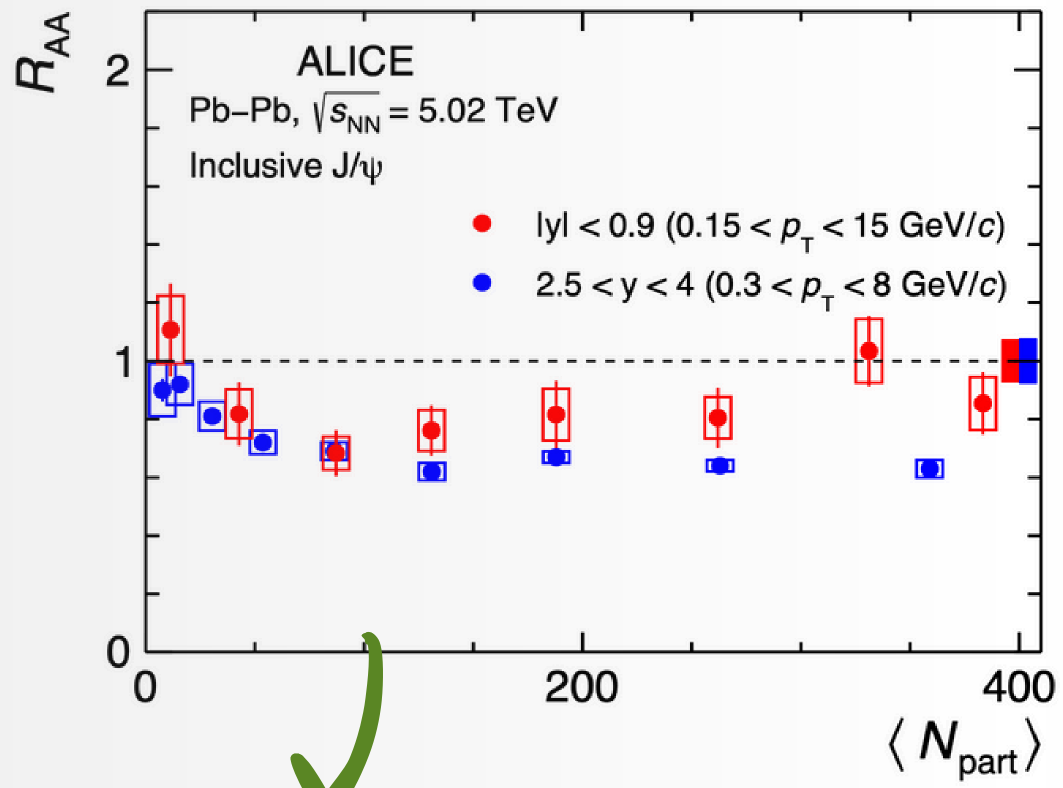
- To measure nuclear modification factors in terms of centrality and transverse momentum

$$R_{AA}(p_T) = \frac{N_{AA}(p_T)}{\langle T_{AA}\rangle \sigma^{pp}(p_T)}$$

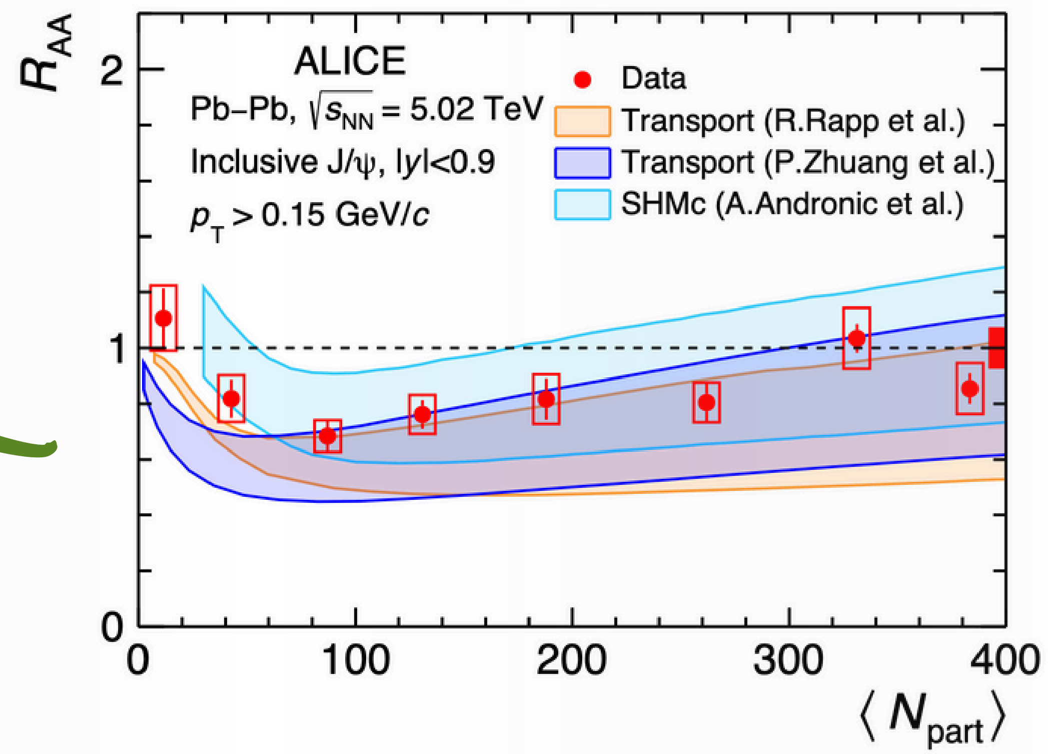
- To observe presence/absence of particulare trends that migth suggest (re)generation or suppression

DATA COLLECTED BY ALICE (2018)
CENTER-OF-MASS ENERGY: 5.02 TeV
INTEGRATED LUMINOSITY: (105 + 51 + 22 + 756)/ μB

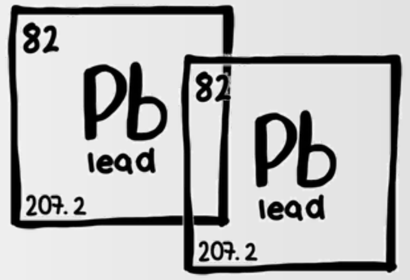
ALICE
CLICK ME



SUPPRESSION SEEMS TO BE MITIGATED WITH THE INCREASE OF CENTRALITY

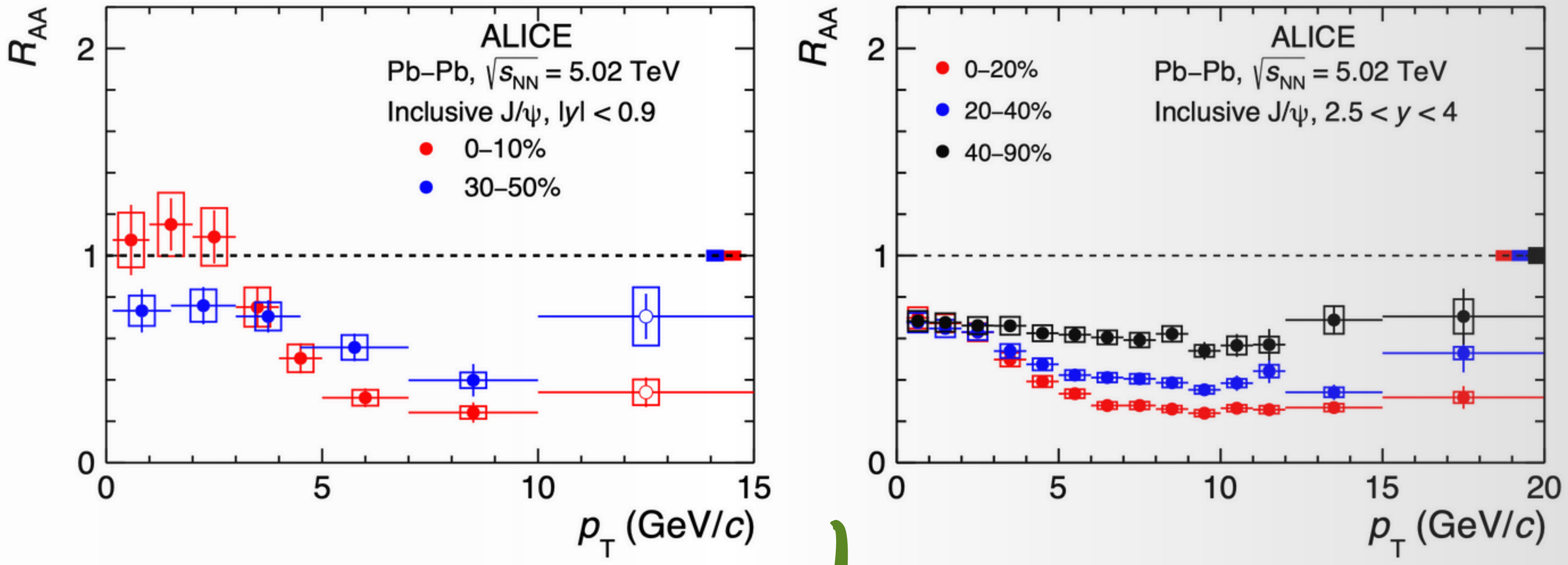


Inclusive J/ψ



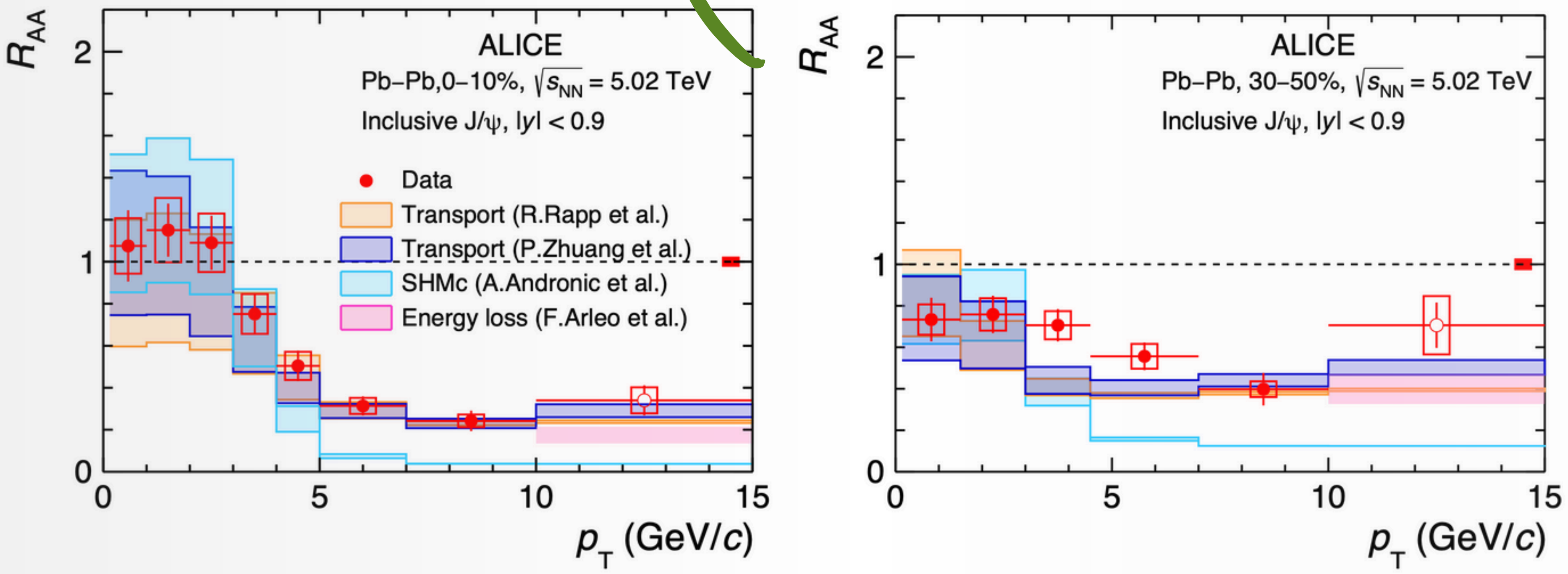
ALICE

CLICK ME

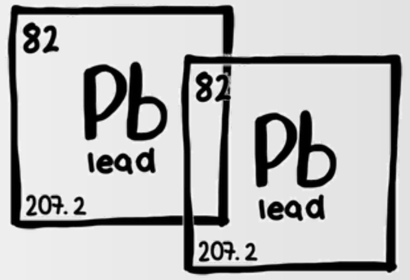


- R_{AA} is high at low p_T (< 5 GeV/c), then strongly suppressed at high p_T.
- Suppression is stronger in central and semicentral collisions.
- In peripheral collisions, R_{AA} is nearly constant, especially at forward rapidity.
- At low p_T: charm quark coalescence reduces suppression.
- At high p_T: dissociation and energy loss dominate.

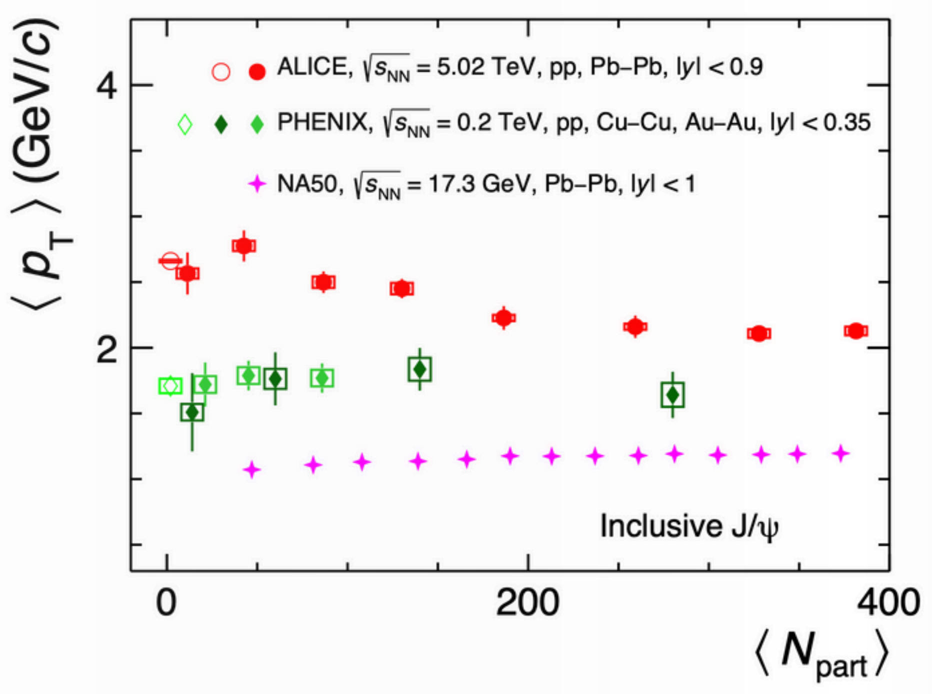
- SHMc model agrees with data at low p_T, but underestimates R_{AA} above 5 GeV/c.
- Discrepancies may stem from missing effects (e.g., primordial or non-prompt J/ψ, underestimated radial flow).
- Transport models better match the data across the p_T range.
- However, at low p_T, transport models struggle to reproduce the detailed R_{AA} (p_T) shape, especially in semicentral collisions — suggesting incomplete understanding of charm coalescence.

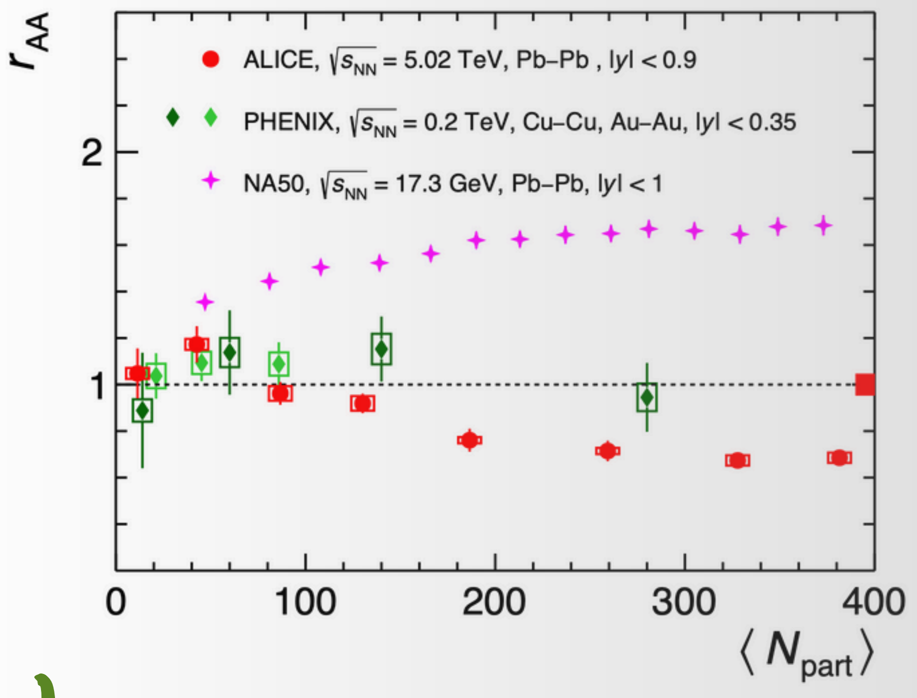


Inclusive J/ψ



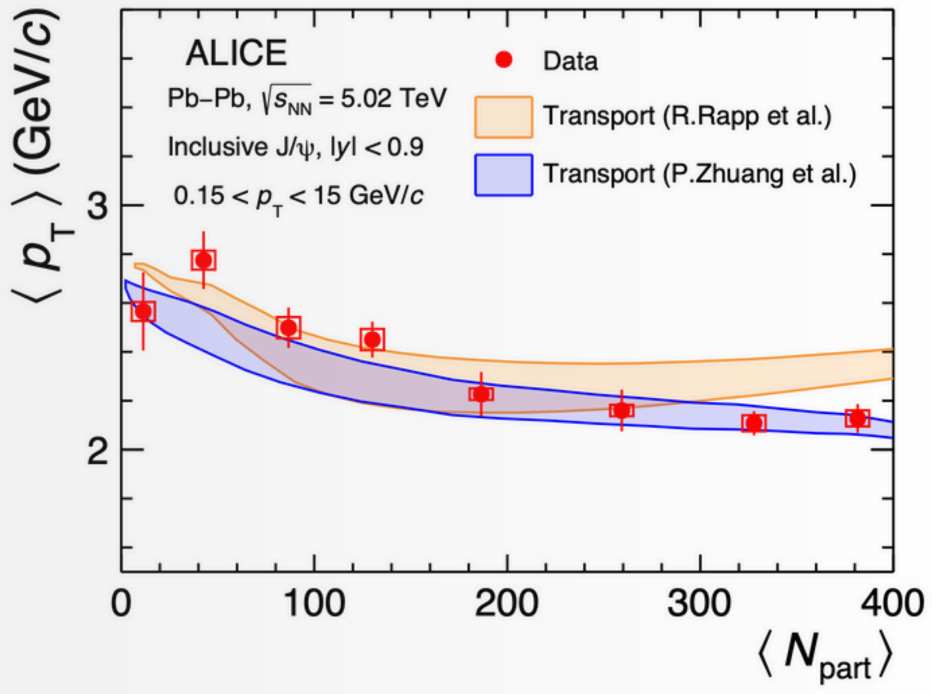
CLICK ME

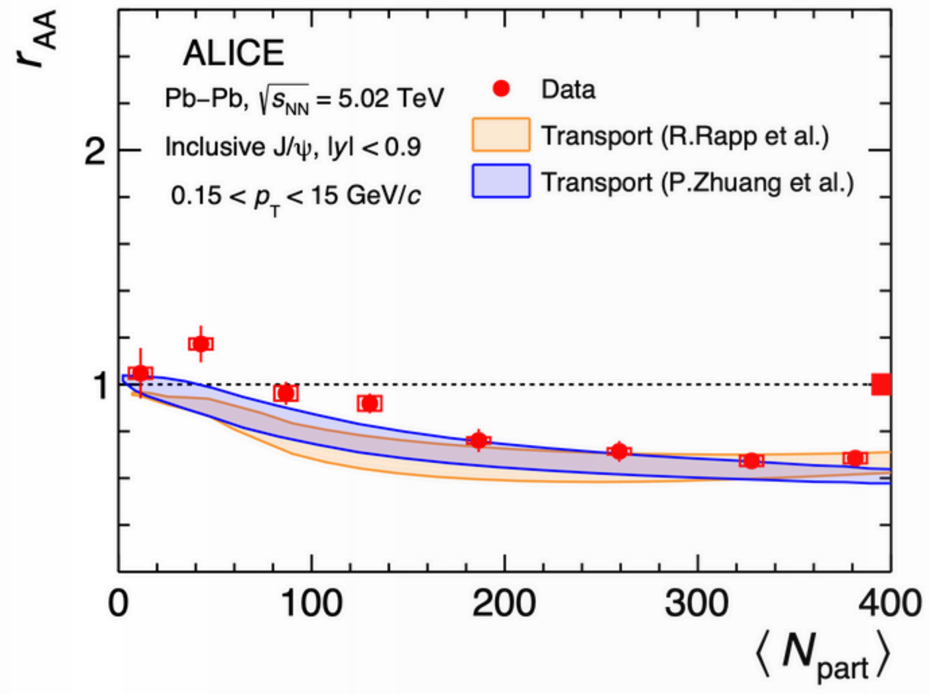




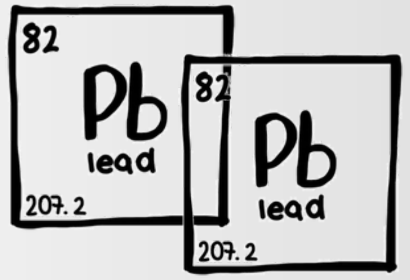
IN GENERAL THERE IS A GOOD AGREEMENT WITH THE MODELS ALSO FOR THESE OBSERVABLES

- ALICE data show a decrease in p_T and r_{AA} from peripheral to central collisions. → (re)generation in central events.
- At RHIC and SPS, no centrality dependence; r_{AA} is flat (RHIC) or increases (SPS).
- SPS increase may be due to cold nuclear matter.
- In peripheral Pb–Pb collisions agrees with pp results at the same energy.





Υ(3S) and suppression

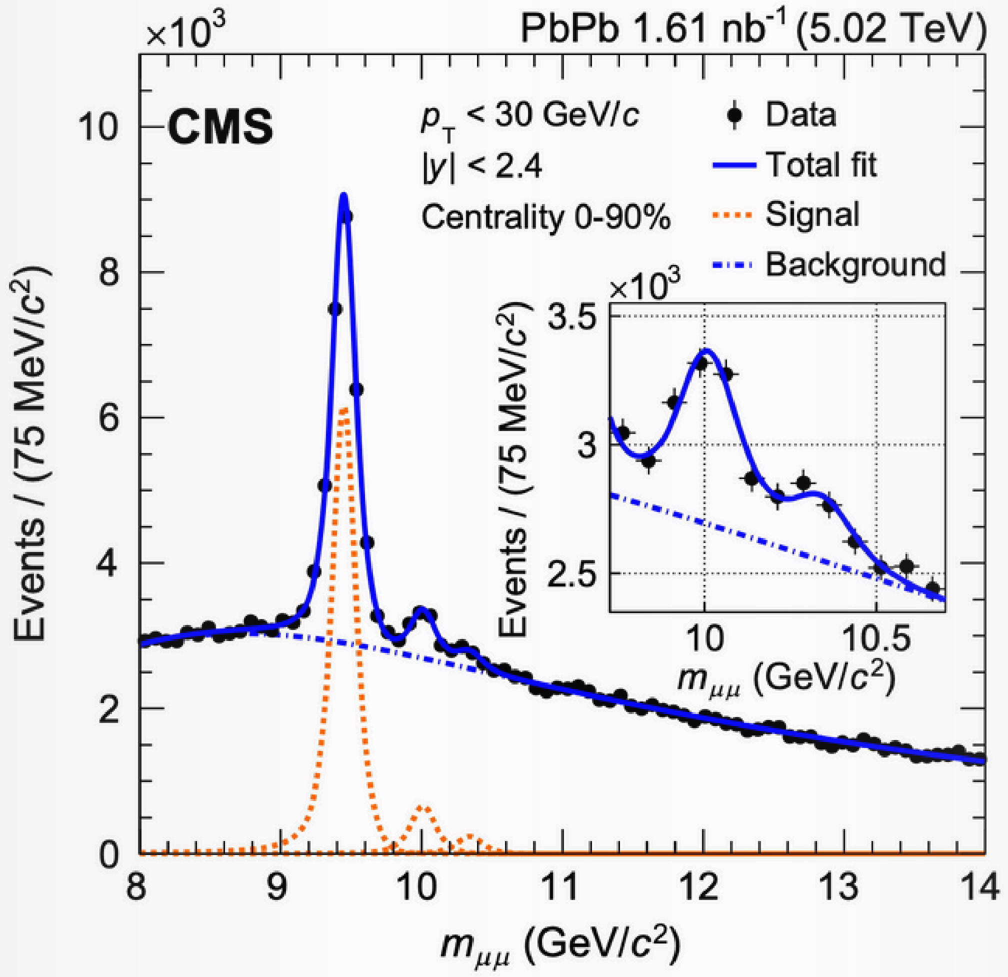


DATA COLLECTED BY CMS (2017-2018)
CENTER-OF-MASS ENERGY: 5.02 TeV
INTEGRATED LUMINOSITY: 1.61/NB

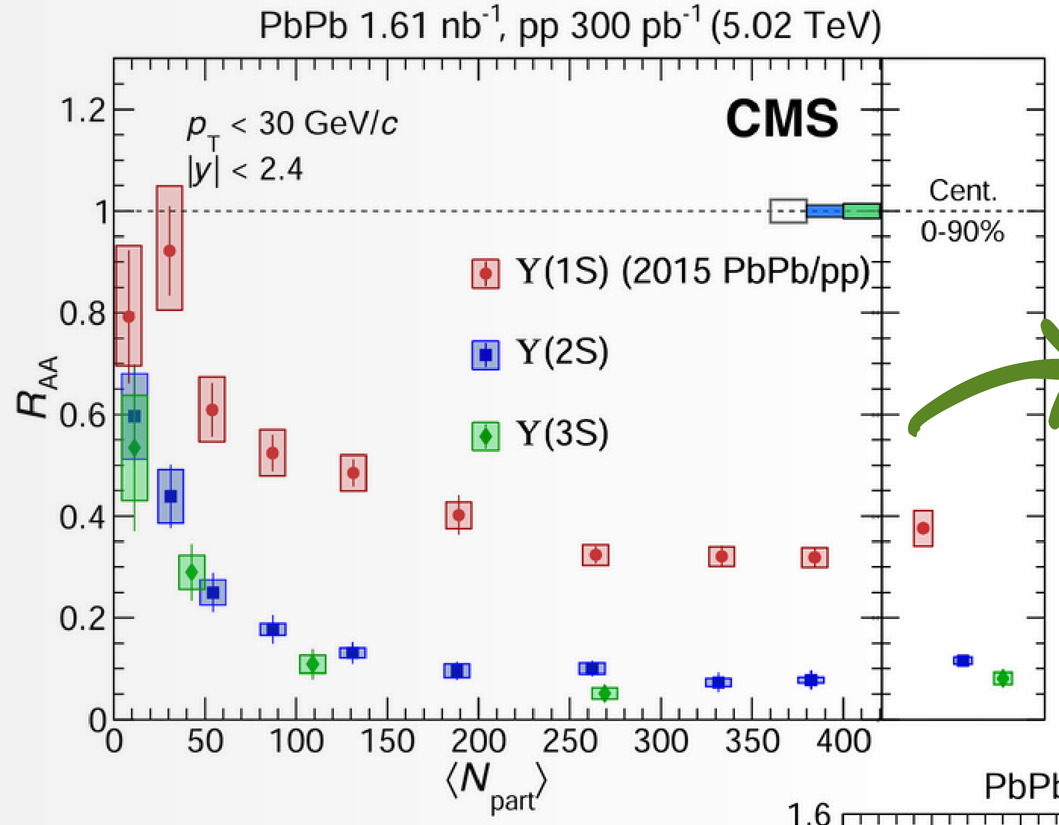
CLICK ME

The goal of the analysis were:

- To observe new bottonium resonances
- To measure nuclear modification factors in terms of centrality and transverse momentum
- To observe presence/absence of particulare trends that migth suggest (re)generation or suppression

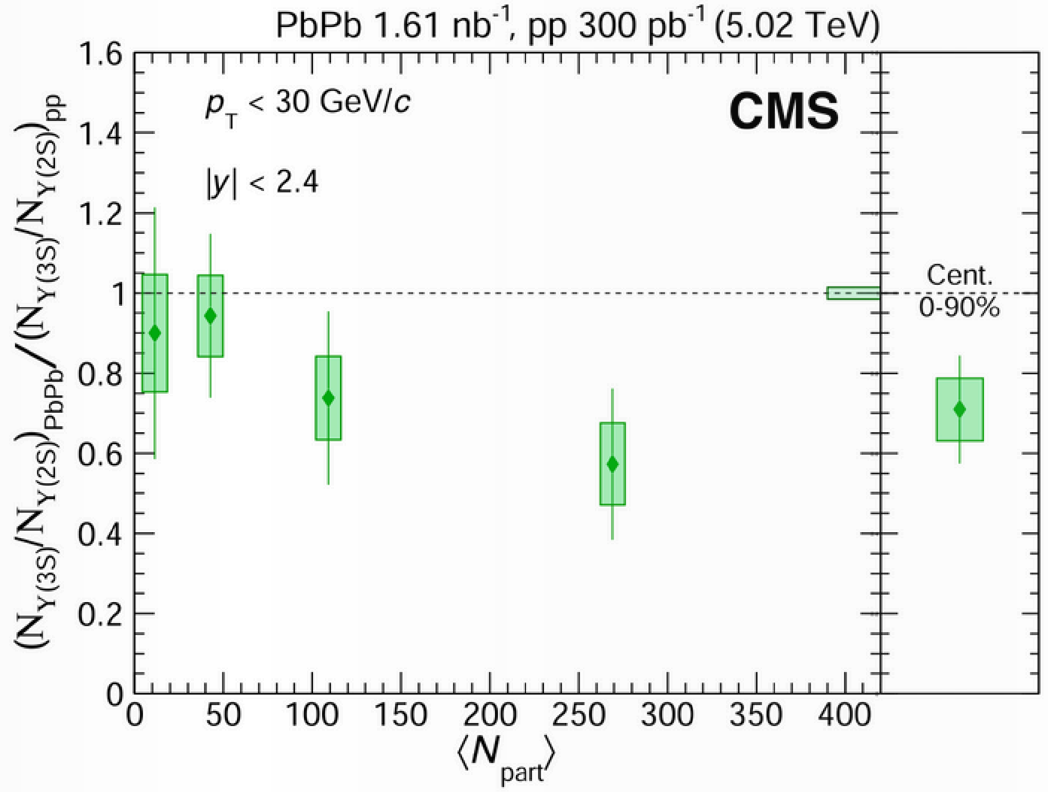


FIRST OBSERVATION OF Υ(3S) IN PB-PB COLLISIONS WITH A SIGNIFICANCE ABOVE 5 STANDARD DEVIATIONS.

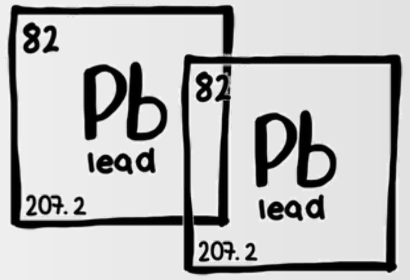


NO PARTICULAR TRENDS THAT INDICATE (RE)GENERATION, INDED THE SUPPRESSION INCREASES WITH THE CENTRALITY

GRADUAL DECREASE TOWARD MORE CENTRAL INDICATING THAT THE SUPPRESSION IS STRONGER FOR THE Υ(3S) MESON INCREASES WITH CENTRALITY



Υ(3S) and suppression



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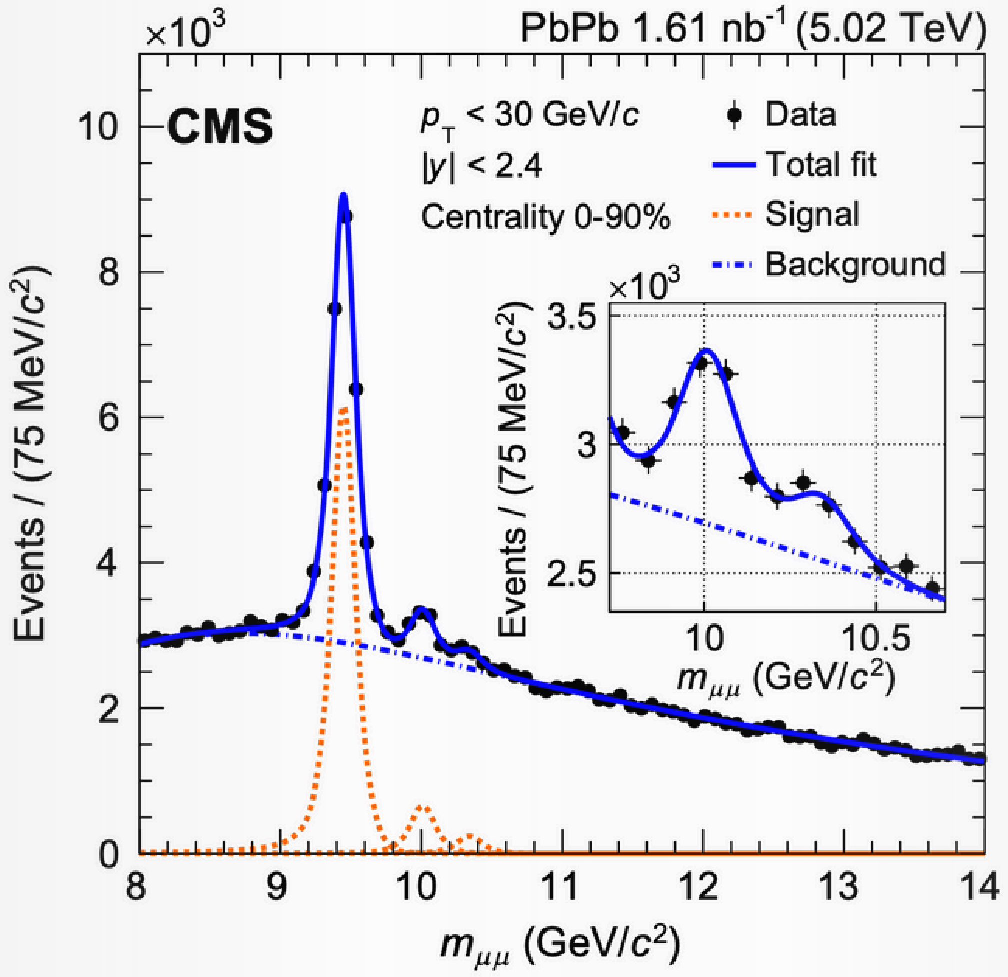

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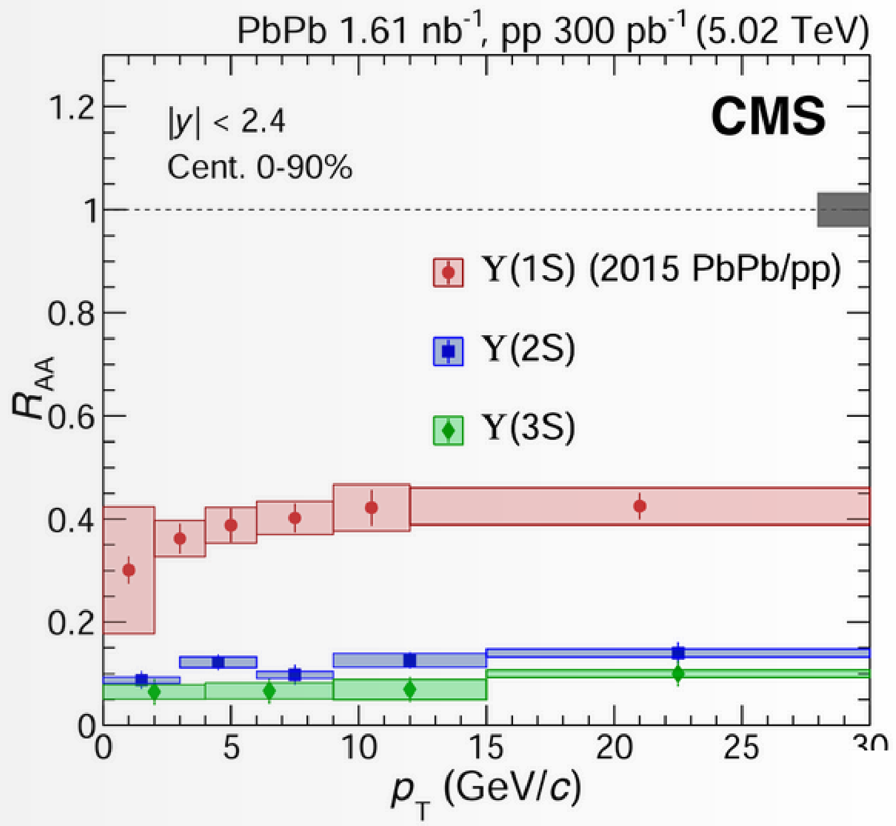
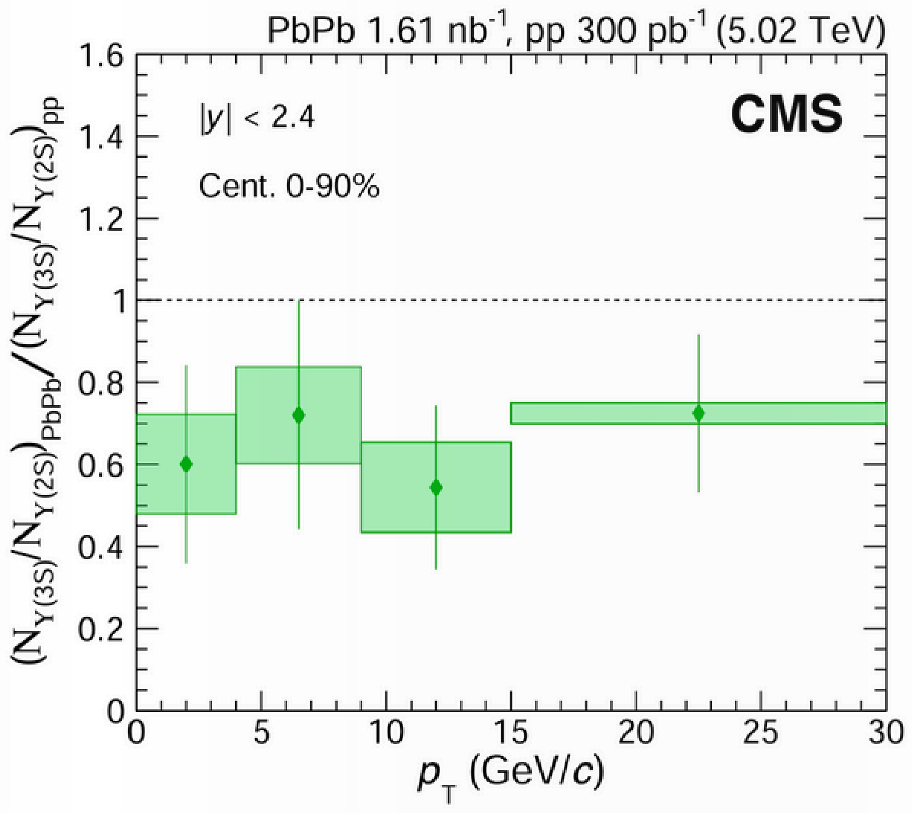


NO SIGNIFICANT DEPENDANCE ON TRANSVERSE MOMENTUM



Summary

THE EUROPEAN PHYSICAL JOURNAL C
Eur. Phys. J. C (2024) 84:169
https://doi.org/10.1140/epjc/s10052-024-12439-9
Regular Article - Experimental Physics

Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 4 October 2023 / Accepted: 12 January 2024

CMS-BPH-22-009
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CMS-BPH-22-006
CERN-EP-2024-058
2024/06/10

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LHCb-CON

Observation of the rare decay $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

PHYSICAL REVIEW LETTERS 133, 022302 (2024)

Observation of the $\Upsilon(3S)$ Meson and Suppression of Υ States in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. Tumasyan et al.*
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(Received 29 March 2023; revised 14 January 2024; accepted

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2023-054
22 March 2023

ALICE

Measurements of inclusive J/ψ production at midrapidity and forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

nature physics
Article

Observation of triple J/ψ me
in proton-proton collisions

CMS Physics Analysis Summary

Contact: cms-pag-conveners-heavyions@cern.ch

2024

Observation of double-J/ψ meson production in collisions at 8.16 TeV

Quarkonia offer an excellent testing ground across all types of collisions to challenge and deepen our understanding of QCD.

They can provide insights into various phenomena such as QED effects, multi-parton interactions, production mechanisms, and (re)generation processes.

Quarkonia are more complex than they may seem to those not working with them regularly — many aspects are still not fully understood.
That means there’s still plenty of work to do… and a lot of fun to be had!

Biblio

- **J/ψ and Υ(2S):**
  - CMS paper
  - ATLAS paper
- **J/ψ in 4 muons:**
  - CMS paper
  - LHCb paper
- **J/ψs in MPI:**
  - CMS paper (p-p)
  - CMS paper (p-Pb)
- **J/ψ & Υ(nS) in Pb-Pb:**
  - ALICE paper
  - CMS paper

THANK YOU

ON BEHALF OF CMS COLLABORATION

MARIA ELENA ASCIOTI | PHD STUDENT
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MARIA.ELENA.ASCIOTI@CERN.CH
MARIAELENA.ASCIOTI@PG.INFN.IT

The pocket formula

POCKET FORMULA

$$\sigma_{\rm DPS}^{pp\to\psi_1\psi_2+X} = \left(\frac{m}{2}\right)\frac{\sigma_{\rm SPS}^{pp\to\psi_1+X}\,\sigma_{\rm SPS}^{pp\to\psi_2+X}}{\sigma_{\rm eff}}$$

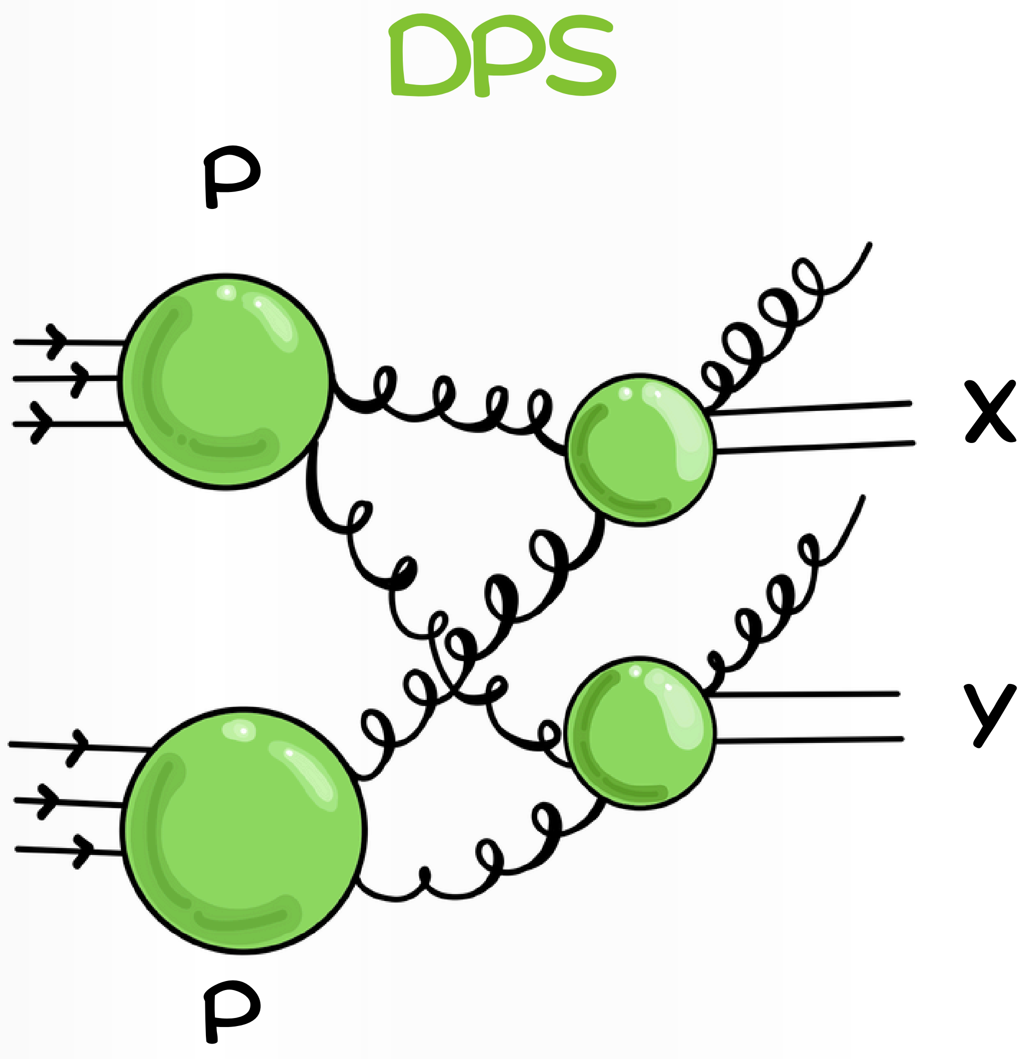
WITH

$$\sigma_{\rm eff} = \left[\int d^2b\, T^2(b)\right]^{-1}$$

WHERE

$$T(b) = \int \rho(b_1)\rho(b_1 - b)\, d^2b_1$$

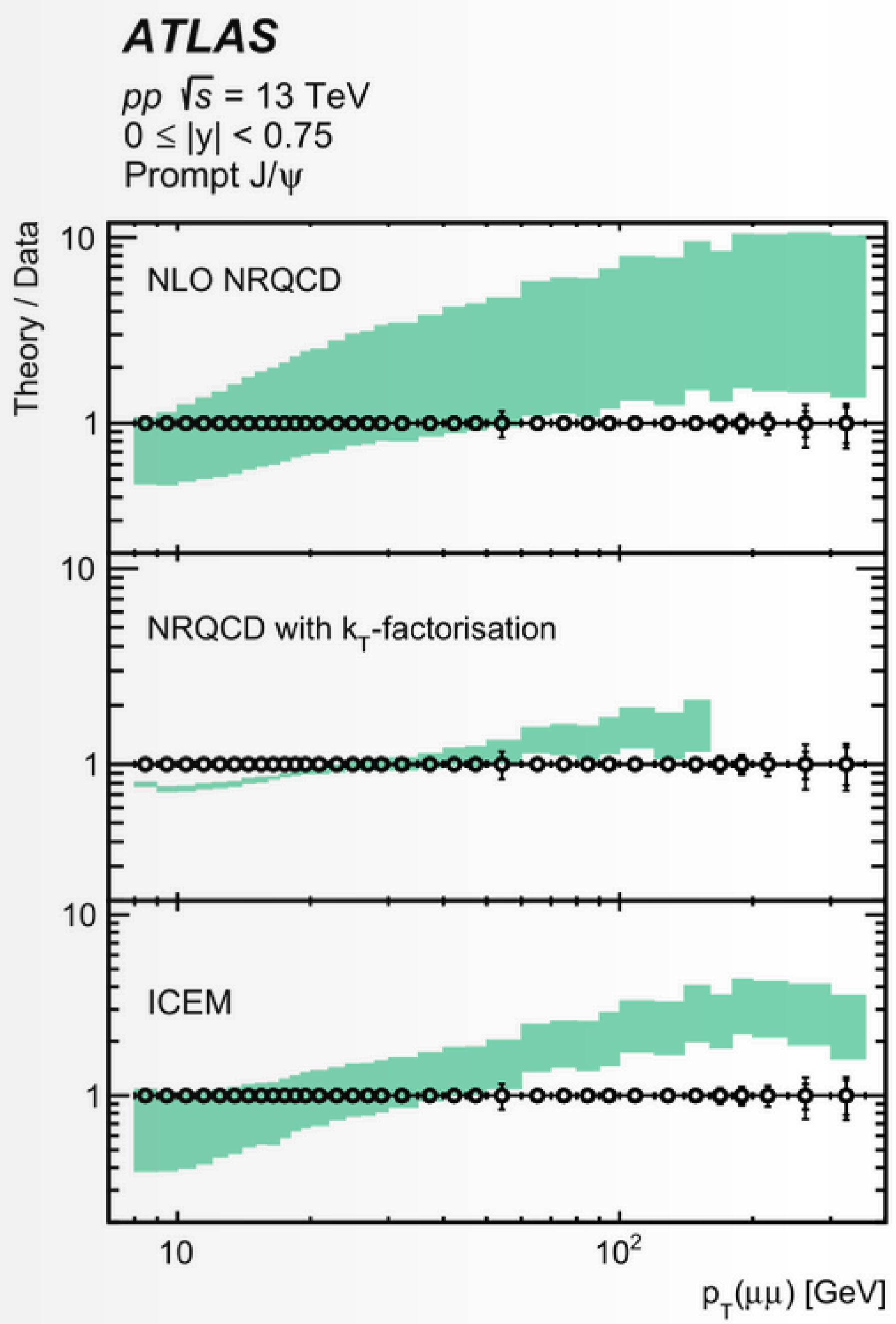
IS THE PP TRANSVERSE OVERLAP FUNCTION AT COLLISION IMPACT PARAMETER B = |B|, WHICH DEPENDS ON THE TRANSVERSE PARTON DENSITY OF THE PROTON

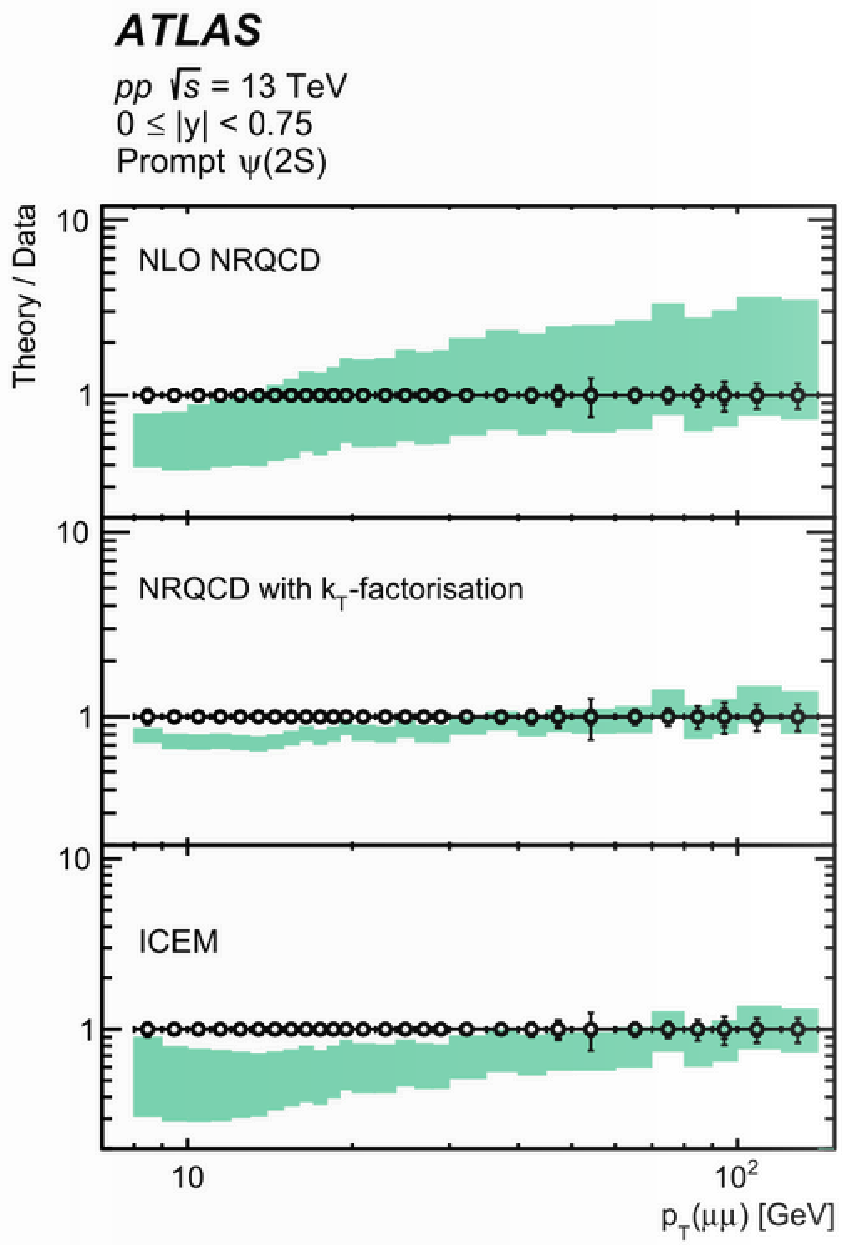


- Double-Parton Scattering (DPS) involves the production of two particles through a double interaction between two partons from the same proton pairs.
- To simplify, the hard scattering is assumed as uncorrelated.
- Described by the pocket formula.

J/ψ and ψ (2S)

- **NRQCD Model (NLO):**
  - Predictions overlap with data within theoretical uncertainties (e.g., scale variations) **but overestimate cross-sections at high p_T .**
- **NRQCD kT-factorisation Model:**
  - Accounts for the transverse degrees of freedom of initial gluons.
  - Predictions (using PEGASUS) compared to data
  - Underestimates cross-sections at low p_T ; **limited agreement at high p_T due to the availability of the gTMD PDF.**
- **ICEM Model:**
  - Assigns a fixed fraction for bound-state formation.
  - Harder p_T spectra than observed in the for both J/ψ and ψ(2S), and t**ends to underestimate the cross-section for ψ(2S)**





J/ψ and ψ (2S)

- **FONLL (Fixed-Order Next-to-Leading Log):**
  - Predictions obtained using default parameters.
  - Matches data well at low p_T, **but overestimates cross-sections for J/ψ at high p_T.**
- **GM–VFNS (General-Mass Variable Flavour Number Scheme):**
  - Based on next-to-leading-order QCD.
  - Similar trends to FONLL but l**arger deviations** from data at high p_T, especially for J/ψ.
- **NRQCD with kT-Factorisation:**
  - Reproduces p_T shapes fairly well but underestimates ψ(2S) production at low p_T.